Chair of Economic- and Business Management

Master's Thesis

Techno-economic assessment of the application of sorption heat storage in single-family houses

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Lehrstuhl für Wirtschafts- und Betriebswissenschaften

Aufgabenstellung

Herrn **Benedikt Franz Maresch, BSc** wird das Thema

Technisch-wirtschaftliche Bewertung des Einsatzes von Sorptionswärmespeichern in Einfamilienhäusern

zur Bearbeitung in einer Masterarbeit gestellt.

Im ersten Abschnitt der Masterarbeit sollen die theoretischen Grundlagen zur Bearbeitung der beschriebenen Problemstellung definiert bzw. eingegrenzt werden. Hierfür soll eine umfangreiche Literaturrecherche durchgeführt werden. Im zweiten Teil soll die Anlage, die zur technischen und wirtschaftlichen Betrachtung dient, beschrieben und deren Wirkungsweise erklärt werden. Weiters sollen die technischen Grundlagen sowie Kennzahlen zur technischen und wirtschaftlichen Vergleichbarkeit erarbeitet und definiert werden.

Im praktischen Teil dieser Arbeit sollen basierend auf einer Marktanalyse die aktuellen Trends am Heizungsmarkt und das Käuferverhalten auf diesem Markt in Österreich untersucht werden. Am Beispiel eines 4-Personen-Haushalts (Einfamilienhaus) sollen Anwendungsfälle mit Vergleichstechnologien definiert werden. Basierend auf praktischen Tests an der realen Anlage soll die Anwendbarkeit der Technologie in unterschiedlichen Kombinationen simuliert werden. Daraus abgeleitet, soll die Wirtschaftlichkeit der Anlage im Anwendungsfall beschrieben und die definierten KPIs berechnet werden. Ein Ausblick auf zukünftige Entwicklungen, mögliche Probleme und eventuell notwendige Verbesserungen soll abschließend gegeben werden.

Leoben, Dezember 2022

Univ.-Prof. Dipl.-Ing. Dr. mont. Wolfgang Posch

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Datum 25.04.2023

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Principle of equality

This paper has refrained from using gender-specific formulations. It is explicitly stated that formulations within this thesis are meant to treat all genders equally.

Abstract

In future energy systems volatile production will be dominant. Heating uses a major share of energy in energy systems. Therefore, the deployment of thermal energy storage is key to successful energy management. Sorption heat storage is a promising technology for long-term storage application.

This thesis examines the potential to store heat in a closed fixed-bed sorption heat storage system on a long-term basis for application on household scale from a technical and financial standpoint and the client's point of view.

Many systems have demonstrated the capability of the system to store heat seasonally. This demonstrator plant showed efficiencies that were high enough to justify this storage technology. Round-trip efficiencies greater than 60% make this technology interesting for various markets. When actively managing the losses RTE close to 100% are possible.

Overall, the technical performance was satisfactory, and Zeolite proved very usable.

LCOH of 350 €·MWh^{-1} to 600 €·MWh^{-1}, LCOS in the range of 600 €·kWh^{-1} to 900 €·kWh^{-1}, storage cost between 36 € ·kWh^{-1} and 76 €·kWh^{-1} and amortization times of 20 to 25 years can be achieved with the presented system. Future improvements and adaptations to the plant layout will improve metrics and achieve market readiness.

Kurzfassung

In zukünftigen Energiesystemen wird die volatile Erzeugung dominieren. Ein großer Teil der Energie in Energiesystemen wird für die Heizung verwendet. Daher ist der Einsatz von thermischen Energiespeichern der Schlüssel zu einem erfolgreichen Energiemanagement. Die Sorptionswärmespeicherung ist eine vielversprechende Technologie für die Langzeitspeicherung.

In dieser Arbeit wird das Potenzial der Langzeitspeicherung von Wärme in einem geschlossenen Festbett-Sorptionswärmespeichersystem für die Anwendung im Haushaltsmaßstab aus technischer und finanzieller Sicht sowie aus Sicht der Kunden untersucht.

Viele Systeme haben die Fähigkeit des Systems, Wärme saisonal zu speichern, nachgewiesen. Auf Systemebene zeigte die Demonstrationsanlage, dass die Wirkungsgrade hoch genug waren, um diese Speichertechnologie zu rechtfertigen. Rundlaufwirkungsgrade von über 60% machen diese Technologie für verschiedene Märkte interessant. Wenn die Verluste aktiv gemanagt werden, sind RTE von nahe 100% möglich.

Insgesamt war die technische Leistung zufriedenstellend. Vom materiellen Standpunkt aus gesehen erwies sich Zeolith als sehr brauchbar.

LCOH von 350 €·MWh^{-1} bis 600 €·MWh^{-1}, LCOS im Bereich von 600 €·kWh^{-1} bis 900 €·kWh^{-1}, Speicherkosten zwischen 36 €·kWh^{-1} und 76 €·kWh^{-1} und Amortisationszeiten von 20 bis 25 Jahren können mit dem vorgestellten System erreicht werden. Zukünftige Verbesserungen und Anpassungen des Anlagenlayouts werden die Kennwerte verbessern und die Marktreife erreichen.

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Abbreviations

°C	degree Celsius
Δh_{ads}	differential enthalpy of adsorption
Δh_b	enthalpy of binding
Δh_C	configurational enthalpy
Δh_{lat}	enthalpy of the phase-change
13X	specific type of synthetic Zeolite
4A	specific type of synthetic Zeolite
AEA	Austria Energy Agency
AEE	AEE INTEC
AEE INTEC	Arbeitsgemeinschaft Erneuerbare Energie - Institut für nachhaltige Technologien
AG	Aktiengesellschaft
Ann	annuity
A_t	annual cost of operation in €
BEV	battery electric vehicle
BF	binder free
C	carbon
Ca	calcium
CAPEX	capital expenditure
$c_{energy,subst}$	cost of substitute energy
CEP	Clean Energy Package for all Europeans
CEP	the clean energy package for all Europeans
c_p	heat capacity at constant pressure
CSP	concentrated solar power
DCF	discounted cash flow
DHW	domestic hot water
DOD	depth of discharge
DWHP	domestic water heat pump
EAG	Energie Steiermark AG
EC	Evaporator-condensor unit
EEX	European Energy Exchange AG
E_t	annual heat production
EU	European Union
FFG	FFG - Die Österreichische Forschungsförderungsgesellschaft
GOT	GreenOne Tec GmbH
H	enthalpy
H_2O	chemical formula of Water
η_{in}	charging efficency in %
η_{out}	discharging efficency in %

HP	heat pump
η_{stor}	storage efficency in %
HTF	heat transfer fluid
$\eta_{total,real}$	real efficency of the system in %
HX	heat exchanger
i	interest rate
I	initial investment
J	Joule
K	Kelvin
k	Kilo, multiplication by one thousand
kg	Kilogram
kJ	Kilojoule
KPI	key performance indicator
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	levelized cost of energy
LCOH	levelized cost of heat
LCOS	levelized cost of storage
LT	lifetime
m	mass
m^3	cubicmeters
mbar	millibar
MFH	multy family home
$M_{t,el}$	produced amount of energy per year in kWh
MW	Megawatt
MWh	Megawatt-hour
NASDAQ	National Association of Securities Dealers Automated Quotations
NPV	net present value
OPEX	operational expenditure
P	power
P2H	Power-to-Heat
Pa	Pascale
P_{char}	charging power
PCM	phase change material
P_{dis}	discharging power
PG	power gradient
PTES	pit thermal energy storage
PV	photovoltaic
Q	heat
Q	quarter
Q_{char}	charging energy
Q_{Cond}	condensation heat
$Q_{heating}$	heating energy

Q_{HP}	heat energy from heat pump
Q_{in}	energy input
Q_{lat}	latent heat
$Q_{loss,pipe}$	heat losses through piping
$Q_{loss,sens}$	sensible heat losses
Q_{out}	energy output
Q_{sens}	sensible heat
$Q_{sensible}$	sensible heat
Q_{store}	stored energy
R_t	net cashflow
RTE	round-trip efficiency
S	entropy
SES	seasonal energy storage
SFH	single family home
SHS	sensible heat storage
SLP	standard load profile
SOC	state of charge
T	temperature
T_A	ambient temperature
TBH	TBH Ingenieure GmbH
T_{ch}	charging temperature
TCM	thermochemical material
TCS	thermochemical storage
T_{disch}	discharging temperature
TES	thermal energy storage
TES4SET	one of the preceding projects at AEE INTEC from 2015
T_S	temperature of the medium stored
USP	unique selling point / unique selling proposition
W	watt
W	work
Wh	watt hours
W_{in}	charged energy, energy input
W_{out}	discharged energy
WP	work package
X	constellation of Zeolite
Y	constellation of Zeolite
YOY	year over year

1 Introduction

In this section, a brief introduction into the problems discussed in this thesis will be given. Also, the methods used during the research process will be discussed. To understand the motivation and the background behind this thesis, the project in which this work is embedded will be presented and explained. The research questions, which act as a basis for the theoretical and practical work will be elaborated and discussed. Finally, the structure of this thesis will be explained.

1.1 Initial situation and problem definition

In recent years, many countries have changed and adapted their energy policies according to the 2015 Paris Agreement. Germany, Austria, and Switzerland all have dedicated plans to phase out coal, nuclear power, and eventually even natural gas. Additionally, they heavily invest in renewable energy resources while needing to ensure a high level of stability and security. Germany's phase out of coal has just recently been confirmed, committing to gas-powered plants, which are ready to run on hydrogen. Switzerland has recently committed to a 2050 net-carbon-zero strategy, while Austria is targeting 2040 net-zero emissions.[1, 2, 3]

There is a growing trend towards using synthetic chemical energy carriers as an alternative to electricity in a variety of fields of application. This is to reduce greenhouse gas emissions. Hydrogen is one such synthetic chemical energy carrier. Specifically in the heating sector, renewable energy will be needed to meet energy demands and emission targets. Along with this change in the energy system, there is an increased need for flexibility. This includes the vast field of efficient management and expansion of grids in the electricity and gas sectors, smart grids for efficient linking of consumers and producers, decentralization of energy production and distribution and increased energy management. The latter includes flexible power plants, active demand side management and the use of energy storage systems. Coupling different energy sectors, e.g., electricity and natural gas, can also lead to a higher degree of flexibility.[4]

As shown in Figure 1, there is a need for storage solutions in various fields of energy. On the production side the contributing factors are the emerging renewable production capabilities. As they are fluctuating producers, compensation is needed for times of low production, when otherwise flexible power plants such as gas fired power plants would be able to supply energy.[5]

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[1] Cf. Seitz, C. et al., https://www.reuters.com/business/sustainable-business/rwe-aims-phase-out-coal-by-2030-2022-10-04/ (Retrieved: 22.12.2022)
[2] Cf. OECD, https://www.oecd.org/regional/RO2021%20Austria.pdf (Retrieved: 22.12.2022)
[3] Cf. OECD, https://www.oecd-nea.org/jcms/pl_74877/achieving-net-zero-carbon-emissions-in-switzerland-in-2050-low-carbon-scenarios-and-their-system-costs (Retrieved: 22.12.2022)
[4] Cf. Stefan Oberholzer (2021), p. 4
[5] Cf. Sterner, M.; Stadler, I. (2014), p. 20

In times of low production, for example in November, when major parts of Europe are experiencing fog, both solar and wind are low on production an additional need for energy is given. Seasonal energy storage would be a possible solution for bridging these gaps in production. In terms of load and operation of energy networks, there is always some sort of discrepancy between where supply is available and where demand is present. However, since transport options are limited and the system is heavily stressed during times of peak demand, solutions are needed. To balance these loads and ease transport decentralized storage facilities could be used, both on a local and international basis.[6]

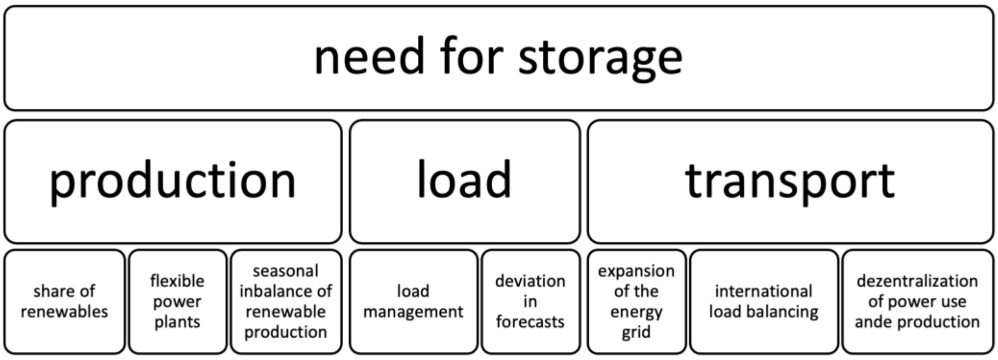

Figure 1: areas of need for storage in the fields of production, load, and transport[7]

The decentralization of energy use and energy production has been identified as a main objective of the European Union (EU) for the domestic sector. The EU needs to make significant efforts to reach its ambitious climate targets by 2030. A 55% reduction in greenhouse gas emissions over 1990 levels, at least a 32% share of renewable energy, and improvements in energy efficiency of at least 32.5% are the target. To reach these goals, the EU announced in 2019 that it would be updating its energy policy framework to enable a sustainable energy transition in the future. This new policy framework is called the Clean Energy Package for all Europeans (CEP). Regulations are included for renewable energy and citizen energy communities, which needed to be implemented within two years. This shows how decentralization is seen as a key concept for decarbonization of the European Union.[8]

1.2 Objective and research question

The objective of this thesis is to investigate the economic and technological potential of sorption heat storage in a closed system as a form of seasonal energy storage.

Is it possible from a technological standpoint to store heat in a closed fixed bed sorption heat storage on a long-term or seasonal basis and if so, is it financially feasible to do so on a household scale either by using surplus electric energy from a photovoltaic system or surplus energy in the electric grid as a service of flexibility?

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[6] Cf. Next Kraftwerke GmbH, https://www.next-kraftwerke.de/wissen/dunkelflaute (Retrieved: 16.01.2023)
[7] Source: adapted from Sterner, M.; Stadler, I. (2014), p. 101
[8] Cf. European Parliament (2018); European Parliament (2019)

1.3 Methodology

According to Figure 2 a detailed literature review has been undertaken to provide a theoretical introduction to the topic. An analysis of past projects at “Arbeitsgemeinschaft Erneuerbare Energie - INSTITUT FÜR NACHHALTIGE TECHNOLOGIEN” (AEE INTEC), especially master's theses, and doctoral theses was conducted as the starting point for the literature review. After reviewing the cited sources, previous publications around sorption heat storage were examined and followed up on. Interviews with colleagues at AEE INTEC, as well as project partners, were conducted to gain a better understanding of what is happening in the field today.

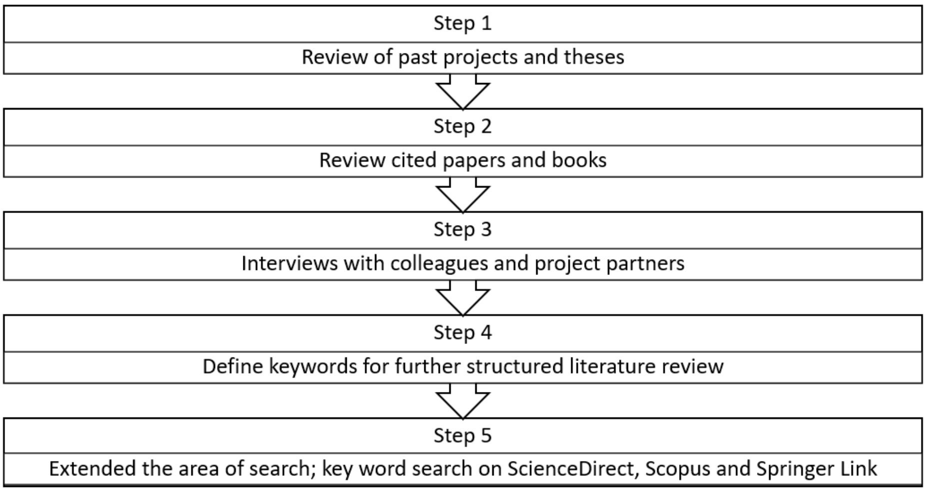

Figure 2: steps of literature review[9]

These findings led to the identification of keywords for a further structured review of the literature. The state of the art in the field of research has then been elaborated. Mainly the research platform ScienceDirect, Scopus, and Springer Link were used, to broaden the field of research.

The practical work was based on the research project FlexModul, which was conducted at AEE INTEC and has been described in detail in section 1.4. of this thesis. Laboratory tests in the field of material research were carried out by team members in parallel with the target of identification of other materials, that could be used for thermal energy storage applications and as an alternative for Zeolite in this project. Component tests were conducted to optimize major parts of the system, such as the evaporator and the condenser. The actual modules will be built and deployed in three different settings and tested in real life conditions on two occasions, one in a multifamily apartment building and one in a complex of 3 single family homes with a centralized heating system. One of the three modules will be installed in the laboratory of AEE INTEC to test edge cases and find the strengths and weaknesses of the system through hardware in the loop approach.

The study on business cases was based on preceding work carried out by Energie Steiermark AG (EAG) and was further developed with a more technical focus and

[9] Source: own illustration

deployment of the system in real life in mind. These business cases were then tested against and in combination with heating systems in financial and technical aspects to verify or falsify the underlying assumptions.

1.4 Project description

This master thesis is embedded in the project “FlexModul”. This project is led by the team at AEE INTEC. The project partners are Energie Steiermark AG (EAG), TBH Ingenieure GmbH (TBH), GREENoneTEC Solarindustrie GmbH (GOT), and Pink GmbH, which are all located in Austria. The project is partially funded by the “FFG - Die Österreichische Forschungsförderungsgesellschaft”, through the Klima + Energie Fonds and partially by the project partners.

Prior to FlexModul, there were several research projects. Starting around 2000 the research around sorption heat storage started with basic demonstration projects and research into material choice. In TES4SET, a preceding project of FlexModul, one of the aspects of the project was to develop and research novel thermochemical materials (TCM) for heat recovery and thermal storage, as well as phase-change materials (PCM) for industrial applications. This project was among the first projects that focused on technology demonstration and deployment in the field. Basic research was conducted, and the first prototypes were built in that phase. In 2015 KÖLL conducted her thesis on this project and laid the foundation for further development. Research in these projects has always been close to industry and real demonstrators have been installed inside buildings for testing.[10]

The project FlexModul is the next in this line and targets real life deployment of the technology with financial feasibility and mass production in mind. The technological side of this project targets further development at a component and system level. Components should be modular, compact, scalable, and cheap, with a focus on scalability and flexibility in deployment in mind. The project aims to further develop the concept to minimize investment costs and maximize its applicability. A maximum investment cost of storage below 27 $€\cdot kWh^{-1}$ is targeted. Therefore, optimization in the areas of material, system complexity, control, building integration, etc., are also key points of the project.[11]

To investigate the full application potential of the technology, specific work will be done to investigate different business case options. This will be done considering the technical and economic performance of the modular storage concept in the application areas of domestic buildings. Tertiary buildings, industry, commerce, and district heating will be compared against domestic buildings to find out if similarities are given and if this technology could be applied.

The demonstration plant will focus on the seasonal aspects of energy storage. The system stores heat from solar thermal collectors or from surplus electricity from photovoltaics (PV) from summer and transfers it to winter. Therefore, it increases the

[10] Cf. AEE INTEC (2019)
[11] Cf. AEE INTEC (2019)

self-consumption of solar energy targeting 100% renewable energy consumption. The storage will be integrated into a single-family house and provide heat for domestic hot water of around 60 °C and space heating of 35 to 45 °C.[12]

Table 1: work packages with the lead company in brackets[13]

WP 1 Management, dissemination, and exploitation (AEE)
WP 2 Component and System Development (GOT)
WP 3 System control, integration, and simulation (TBH)
WP 4 Demonstration (AEE)
WP 5 Business Cases (EAG)

From a project management perspective, FlexModul is split into five work packages (WP), with each project partner leading one. The packages can be found in Table 1 with the lead in brackets. The Gantt chart in Figure 3 illustrates the progress of the project over time. It is planned that the program will run from May 2021 through April 2024, with a total duration planned for three years.[14]

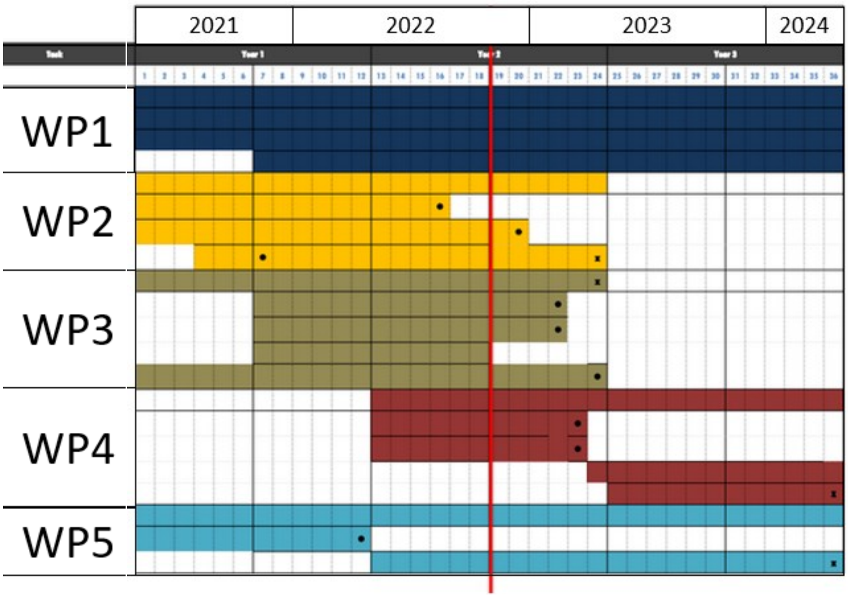

Figure 3: Gantt-Chart of the project FlexModul; the red line indicates the status at the beginning of this thesis[15]

This thesis primarily focud on the WP5 and was based on previous work from WP2 and WP3. WP5 focused on the business aspects of this project and its technologies. The target was the investigation of possible business cases for several use cases.[16]

The definition of technical and economic KPIs for business cases and structuring and assessment of the business cases were elaborated in section 4, based on a literature review and a market analysis. For this thesis, the sorption heat storage system that was

12 Cf. AEE INTEC (2019)
13 Source: own illustration
14 Cf. AEE INTEC (2019)
15 Source: own illustration
16 Cf. AEE INTEC (2019)

proposed, discussed, and analyzed in this thesis is named after the project and is called FlexModul.

1.5 Structure of the thesis

The thesis is split into three distinct parts. The first one focuses on the theoretical aspects of the topic and is based on an extensive literature review. The technical and economical foundation for practical work is laid in this section. KPIs for comparison will be defined in this section. The second part of this thesis is the foundation for the practical work is laid. The plant layout, its working principles and the business cases will be described here.

The third part of this thesis is based on an extensive market analysis. This lays the foundation for the further technological and financial performance comparison. Practical work like simulations and real-life tests are implemented and realized based on the use cases defined because of the market analysis. The results are compared in an extensive financial analysis.

A summary and analysis of the work are presented in the third chapter, and conclusions are drawn because of these analyses. There is an outlook on what the future holds in terms of developments, potential problems, and improvements that might be necessary.

2 Theoretical Part

The following section focuses on the theoretical aspect of the topic energy storage and sorption energy storage. First, an introduction into the topic of thermal energy storage (TES) is given, including an overview of various methods, and the basic principles that all methods have in common. Then an introduction to sorption technology is given, including several methods for working with sorption materials. The potential of sorption energy storage reasoning behind the decision for sorption energy storage is later discussed. To be able to compare several technologies, an introduction into comparison of energy technologies is given. Basic reference technologies will be described, and reference scenarios will be developed for later comparison.

2.1 Technological Basics

In this chapter, the technological aspects of the topic are described. Starting with the basics of thermal energy storage an introduction is given. Later, the principles of sensible and thermochemical heat storages are discussed in detail, leading to the idea of sorption heat storage.

Without energy storage systems, energy supply is almost impossible. They are an elementary building block of our energy system. The role that a storage system plays in the energy system is often discussed: Are energy storage systems part of the energy networks or are they "producers" and "consumers"? Where are the costs of storage located? Definitions help classify storage in terms of energy economics. How storage and energy storage can be defined, their benefits recorded and classified according to physical, energetic, temporal, spatial, and economic criteria is discussed in this chapter.[17]

2.1.1 Basics of thermal energy storage

Energy storage can be classified based on different parameters. The most crucial factors are as follows:

- principle of storage, e.g., chemical, physical[18]
- duration or timespan of storage, e.g., seasonal, daily[19]
- spatial, e.g., centralized, decentralized[20]
- type of energy stored, e.g., electric energy, heat[21]

[17] Cf. Sterner, M.; Stadler, I. (2014), p. 42
[18] Cf. Oertel, D. (2008), p. 31
[19] Cf. Sterner, M.; Stadler, I. (2014), p. 35
[20] Cf. Sterner, M.; Stadler, I. (2014), p. 35
[21] Cf. Oertel, D. (2008), p. 31

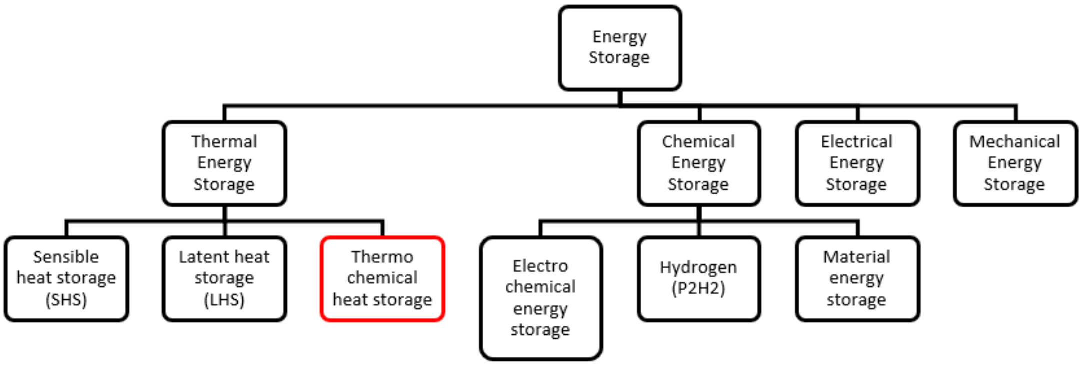

Figure 4: classification of energy storage technologies based on working principle[22]

A brief overview based on the type of energy store is given in Figure 4. The field of thermochemical energy storage can be attributed to chemical and thermal energy storage. As it is primarily a storage of potential heat energy, most authors attribute it to the latter one, as highlighted in red. This thesis focuses on TES exclusively. This can be attributed to the vast size of the field of energy storage and the different physical working principles.[23] Storage concepts like pumped hydro, and chemical energy storage like hydrogen or lithium-ion batteries will not be discussed in this thesis.

The field of TES can be narrowed down on the factors mentioned above. In this thesis sensible heat storage (SHS) and seasonal energy storage (SES) in the form of thermochemical heat storage will be further elaborated. SHS will also be further discussed, as they are the most applied type of TES. Almost everybody worldwide has contact with them every day. SES are seen as keystone concept for decarbonizing our energy system and are hence a topic of intensive ongoing research.[24]

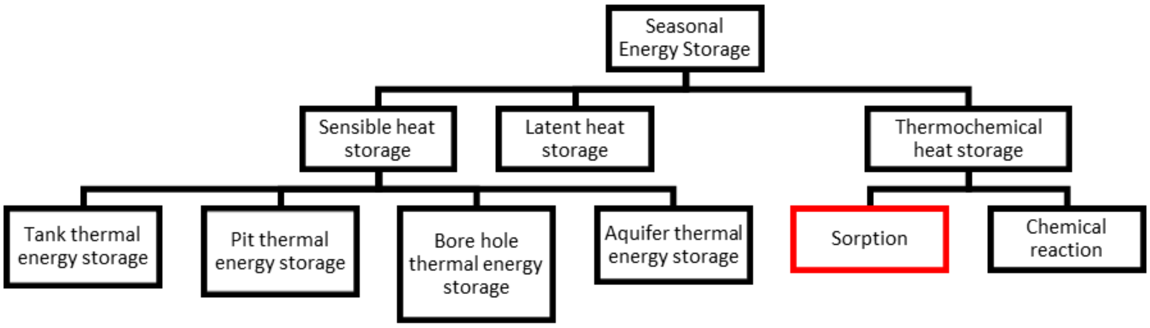

Figure 5: hierarchical classification of seasonal energy storage types [25]

As shown in Figure 5, sorption is in terms of energy storage, a part of thermochemical heat storage (TCS). However, due to the nature of the material, it is also capable of storing a considerable amount of energy in the form of sensible heat, only for a short amount of time. This will be later discussed as a potential strategy for operating the sorption storage.[26]

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[22] Source: adapted from Goeke, J. (2021), p. 17
[23] Cf. Goeke, J. (2021), p. 18
[24] Cf. Sterner, M.; Stadler, I. (2014), p. 128
[25] Source: adapted from Yang, T. et al. (2021), p. 2
[26] Cf. Goeke, J. (2021), p. 17

2.1.2 Basics of sensible and latent heat storage

In this section two distinct types of TES will be discussed: sensible heat and latent heat storage. Sensible heat storage (SHS) is one of the most common storage technologies, as most people use this technology daily. Sensible heat refers to a form of energy humans can feel and relate to as temperature, in contrast to chemical or electrical energy. The key principle of SHS is a medium, which is warmed up relative to its surrounding. This can be achieved through any form of heat flow. The amount of energy stored can be calculated with Formula 1. Q (kJ) is the amount of energy stored and is directly proportional to the mass m (kg), the thermal heat capacity c_p ($kJ \cdot kg^{-1} \cdot K^{-1}$), and the temperature difference ΔT (K) to the surrounding or the relative difference to the return flow, which is T_2 minus T_1.[27]

$$\boldsymbol{Q = m \times c_p \times \Delta T = m \times c_p \times (T_2 - T_1)}$$

Formula 1: stored energy in a material through temperature difference without phase change[28]

As shown in Figure 6 there are certain materials that can be used specifically well for energy storage due to high heat capacity. On the left side typical building materials, such as sand, cement, concrete, or clay, are clustered. In the middle red circle typical fluids of daily use like olive oil, motor oil, glycol is shown. Finally on the top right saltwater and pure water are shown. Both the energy density per volume and the heat capacity per mass are the highest for water in terms of daily materials. Therefore, it can be considered the best liquid sensible thermal energy storage material for application in the temperature window from +4 °C to +100 °C. For applications below the water freezing point, mineral oils or water-glycol mixtures are used. For applications above 100 °C liquid metals, molten salt and mineral oils are used. Working areas of salts go as high as 580 °C, but are limited to a minimum temperature above melting point of around 220 °C. [29,30]

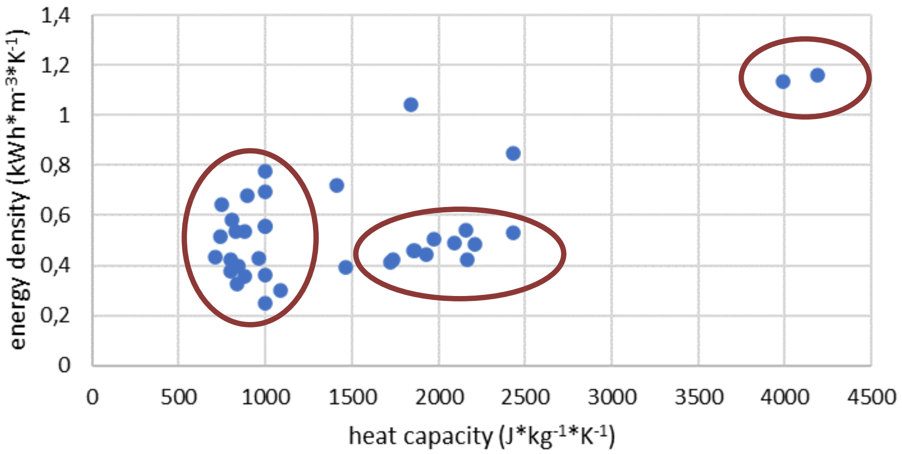

Figure 6: gravimetric energy density vs. heat capacity of various materials [31]

[27] Cf. Sterner, M.; Stadler, I. (2014), p. 537
[28] Source: Sterner, M.; Stadler, I. (2014), p. 541
[29] Cf. Sterner, M.; Stadler, I. (2014), p. 600
[30] Cf. Gunasekara, S. N. et al. (2021), p. 16
[31] Source: own illustration, adapted from Sterner, M.; Stadler, I. (2014), p. 600 pp.

In the case of sensible heat storage, the energy stored is directly proportional to the temperature difference of the inlet and outlet temperature, which requires high temperatures to storage high amounts of energy. The temperatures can range from 0 °C up to 100 °C for water storage tanks up to more than 1000 °C in the case of hot sand or molten rock storage systems.[32]

The storage of thermal energy is always associated with losses of energy. A constant flow of heat, driven by the thermodynamic potential of the temperature difference, flows from the heat source to the heat sink until a steady state and temperature equilibrium is reached. In applications of short-term heat storage, the energy losses are much less of an influence than for storage periods of weeks or even seasonal storage. Therefore, the application determines the importance of the losses and their prevention. In Figure 7, the typical losses of a cylindrical sensible heat storage are shown. Although the shell losses predominate with up to 80%, the connection losses must be considered too. In addition to the proportional loss areas of a storage tank, loss mechanisms within a storage tank cause usable energy to dissipate. One common problem is the mixture of layers within the storage tank, which can be a result of a mass flow into the tank. Installations like baffles can reduce the mixing.[33]

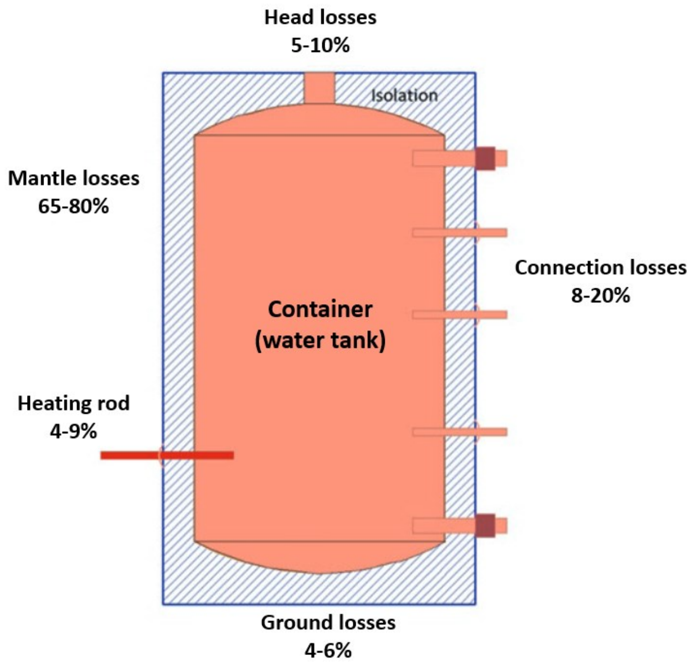

Figure 7: areas of losses of a sensible heat storage tank [34]

From a physical point of view, the term "energy loss" is not correct since energy cannot be consumed or lost, but only converted into another form of energy. Therefore, the term "energy storage" is not quite correct, since energy is retained in any case, but may no longer be usable. Consequently, the term exergy is introduced. Exergy describes the portion of energy that can be converted into other forms of energy without restriction under ambient conditions. Exergy is usable energy in relation to the surrounding. The

[32] Cf. Sterner, M.; Stadler, I. (2014), p. 600 pp.
[33] Cf. Goeke, J. (2021), p. 98
[34] Source: adapted from Goeke, J. (2021), p. 98

higher the temperature difference between the fluid in the storage tank and the ambient temperature, the higher the exergy content and the more valuable the heat becomes. The term anergy, on the other hand, describes the proportion of energy that cannot be used. When considering a lossy charging, storage and discharging process of a TES device, the anergy content increases and the exergy content decreases. The sum of the anergy and exergy content, on the other hand, remains constant.[35]

$$Energy = Exergy + Anergy$$

Formula 2: general formula for exergy and anergy[36]

The exergy content depends on the heat quantity Q (J; Wh), the temperature of the medium stored T_S, and the ambient temperature T_A. For simplicity, the colloquial terms energy storage, heat quantity, etc. will be used in the following chapters instead of exergy and its equivalents.[37, 38]

When considering the losses related to TES, the heat flux through the wall and the insulation plays a significant role.[39] The most crucial factor for heat losses of a storage is the surface area. Since the surface area can vary at a constant volume depending on the shape, there are optimum ratios of length of geometric bodies such as cuboids, tetrahedra or cylinders. For a given volume the sphere has the smallest surface to volume ratio. As demonstrated in Figure 8 there are major differences in the surface area of an object, and for energy application important, in the surface of a storage tank. As the heat loss is primarily dominated by the heat flux through the surface area of a given tank, this needs to be minimized. Most storage tanks are therefore built in the shape of a cylinder. A spherical shape would be even better. However, other constraints also need to be considered, which is why this optimum cannot be achieved.[40]

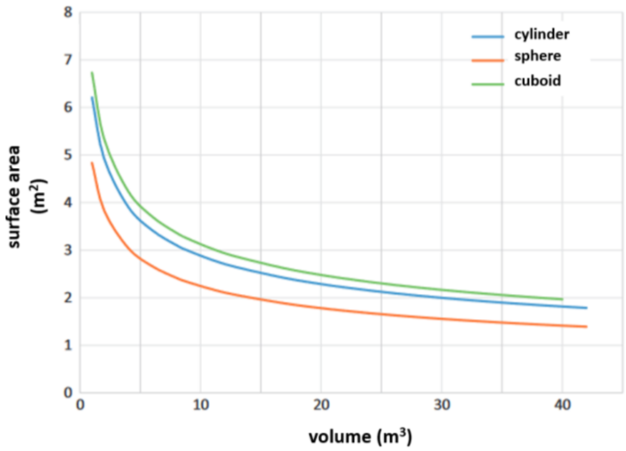

Figure 8: surface area to volume of a storage vessel[41]

For FlexModul, these basic characteristics were also considered and respected. Hence, all tanks that have a relatively high temperature of up to 60 °C, such as the condenser,

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[35] Cf. Goeke, J. (2021), p. 29
[36] Source: Goeke, J. (2021), p. 38 pp.
[37] Cf. Goeke, J. (2021), p. 29
[38] Cf. Goeke, J. (2021), p. 38
[39] Cf. Goeke, J. (2021), p. 97
[40] Cf. Goeke, J. (2021), p. 108
[41] Source: Goeke, J. (2021), p. 108

the evaporator or the water storage tank have a spherical or cylindrical shape. The hottest components, however, have a cuboid shape. The cuboid shape is essential for economic reasons, to be able to position the tanks close to each other and to achieve the modularity and scalability required in the project. A cuboid container uses less floor area than a spherical container, which means, it takes up less space in the customers houses. The thermal disadvantage of cuboid containers is present and needs to be compensated through insulation and strategically positioning the tanks in relation to each other.[42]

Contrary to SHS, latent heat storages or phase change materials (PCM) store and release heat by changing the aggregate state of the material. In general, Q_{lat} (kJ) is defined as the amount of energy stored or retrieved from the phase change, m is the mass of the material, and Δh_{lat} ($kJ \cdot kg^{-1}$) is the material specific phase change enthalpy. This means, the amount of energy stored is only dependent on the mass of the material and the choice of the material. It is not, however, dependent on the temperature.[43]

$$Q_{lat} = m \times \Delta h_{lat}$$

Formula 3: energy stored in a phase change material (PCM)[44]

In Figure 9 PCMs show a high energy storage capacity while remaining at a constant temperature level for a long time. In general, there are two distinct operating scenarios for PCMs. One operating scenario allows a storage system to operate at constant temperature, as demonstrated in Figure 9. The other one uses salts and allows energy to be stored with little losses over a long period of time in the form of subcooled liquid salts. Subcooled salts are molten salts, which are then cooled down to ambient temperature while remaining in the liquid state. The stored energy can then be released through triggering the solidification of the material.[45]

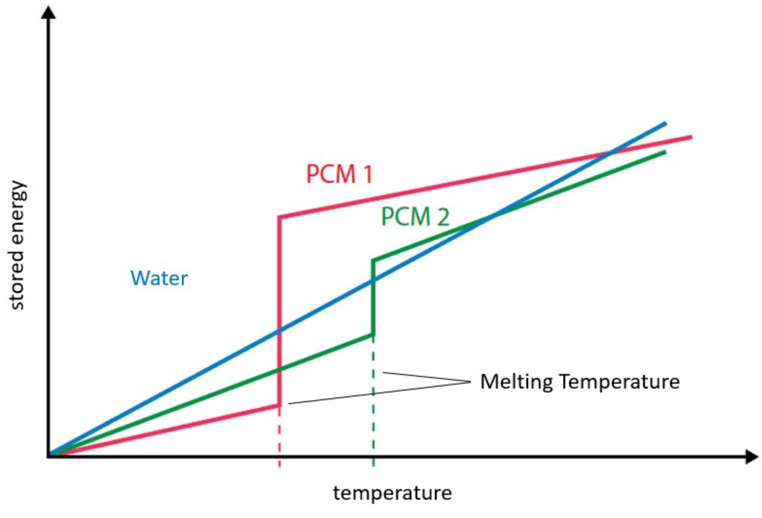

Figure 9: example of PCMs in comparison to water[46]

[42] Cf. Goeke, J. (2021), p. 108
[43] Cf. Sterner, M.; Stadler, I. (2014), p. 714
[44] Source: Sterner, M.; Stadler, I. (2014), p. 714
[45] Cf. Sterner, M.; Stadler, I. (2014), p. 133
[46] Source: adapted from Sterner, M.; Stadler, I. (2014), p. 714

Using latent heat storage systems, for example in air conditioning of rooms integrated into building mass, allows the building to be heated and cooled at constant temperature, which greatly improves comfort. Latent heat storage technologies are currently mainly used for specific applications. In the energy system, they do not play a significant role in storing large amounts of energy. With load management, they can potentially store fluctuating quantities of electricity without affecting user comfort when used in conjunction with air conditioning systems. Latent heat storage has some advantages over sensible storage. For example, more thermal energy can be conserved at small temperature differences than with sensible storage. The melting temperature of the various material classes ranges from -40 °C to well over 1000 °C. Due to the high storage capacity, latent heat storage systems can be built much more compactly than sensible heat storage systems. However, as the storage is related to a given temperature, it is always associated with heat losses, which limits the potential to store energy over long periods dramatically.[47]

As a latent heat storage method, ice storage uses melting cold to charge it and solidification heat to discharge it. The storage and retrieval of heat is accomplished through heat exchangers coupled with heat pumps (HP) and solar collectors, as demonstrated in Figure 10.[48]

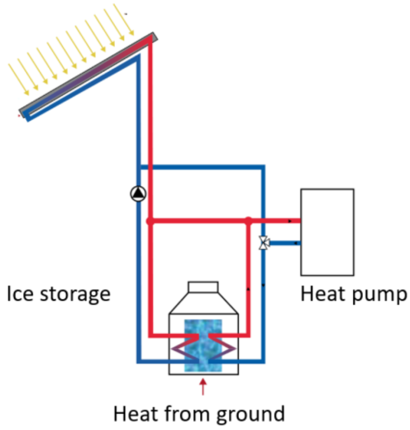

Figure 10: example for latent heat storage in housing application[49]

Latent heat storage has some advantages over sensible storage. For example, more thermal energy can be conserved at small temperature differences than with sensible storage. SHS and latent heat storage do have a potential for seasonal energy storage. The idea of heating up the system in the summer and using this stored heat in winter is simple and convincing. In the past years many projects have demonstrated the technological and economic feasibility. For sensible heat storage, the most common forms are pit thermal energy storage systems (PTES).[50]

These systems are basically large cuboid, spherical or truncated pyramid containers, that are either buried under ground or built in the ground with an insulating layer on top, as demonstrated in Figure 11. All construction types need to be heavily insulated all

[47] Cf. Sterner, M.; Stadler, I. (2014), pp. 37, 133, 538
[48] Cf. Sterner, M.; Stadler, I. (2014), p. 133
[49] Source: adapted from Sterner, M.; Stadler, I. (2014), p. 713
[50] Cf. Xiang, Y. et al. (2022), pp. 2–5

around. The advantages of PTES are the simple working principle and the simple scalability. Disadvantages are constant energy losses, that can only really be compensated through minimizing the ratio of surface to volume through building bigger. Therefore, PTES are only used in large scale applications, for example by heating grid operators.[51]

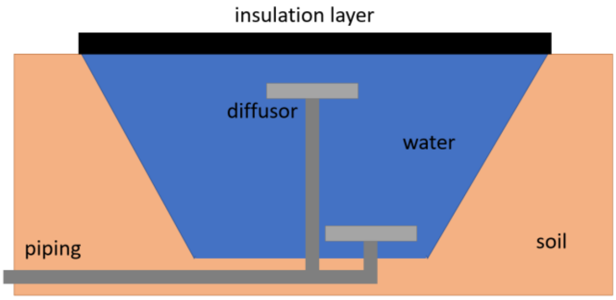

Figure 11: basic layout of a PTES, with the insulating lid on the top[52]

2.1.1 Thermochemical Heat Storage

The term thermochemical energy storage refers to chemically reversible reactions in which the reaction products can be separated and stored over an extended period. The energy is stored in an endothermal reaction and is released through an exothermal reaction. Due to the separation of materials, no storage losses occur. The stored energy is only released during the discharge process, where a reaction, a mass and a heat transfer take place. The primary reason, why currently a lot of research is conducted can be seen in Figure 12.[53]

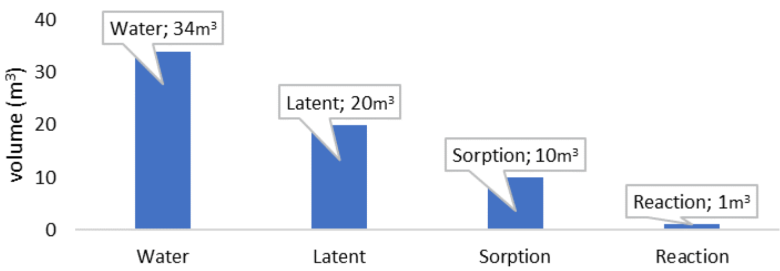

Figure 12: comparison of equivalent energy storage capacity[54]

Thermochemical, especially sorption heat storage, have significant higher storage capacities than conventional systems like SHS in water. Only chemical reactions can achieve even higher energy densities.[55] The concept of sorption heat storage will be elaborated in this section, starting with general definitions and mechanisms.

Thermochemical energy storage systems allow very high energy storage densities, but are currently hardly used in practice, as this technology is still at research stage.[56] This

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[51] Cf. Xiang, Y. et al. (2022), p. 8
[52] Source: own illustration, adapted from Xiang, Y. et al. (2022), p. 8
[53] Cf. Sterner, M.; Stadler, I. (2014), p. 538
[54] Source: own illustration, adapted from Yu, N. et al. (2013), p. 491
[55] Cf. Sterner, M.; Stadler, I. (2014), p. 538
[56] Cf. Sterner, M.; Stadler, I. (2014), p. 538

is demonstrated in relation to sensible and latent heat storages in Figure 13, where the state of development in the various fields is shown in relation to the energy density of the technology.

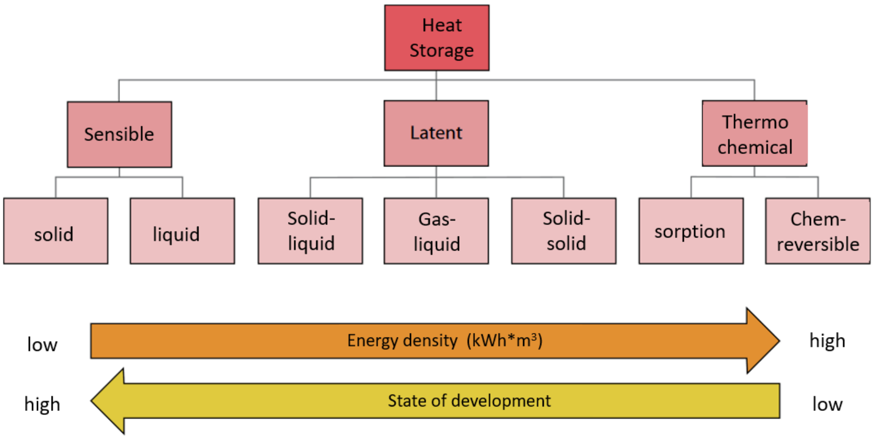

Figure 13: state of development of storage technologies[57]

Thermochemical heat storage has a very high energy density, however, the state of development is rather low, as other technologies were the focus of research in prior years. As shown in Figure 14, that research is steadily increasing in the field of energy storage in general. Latent heat and sensible heat storage have been in the center of interest. In the more recent years, however, publications started to rise and gain momentum.[58] This will be discussed in detail in section 2.2.

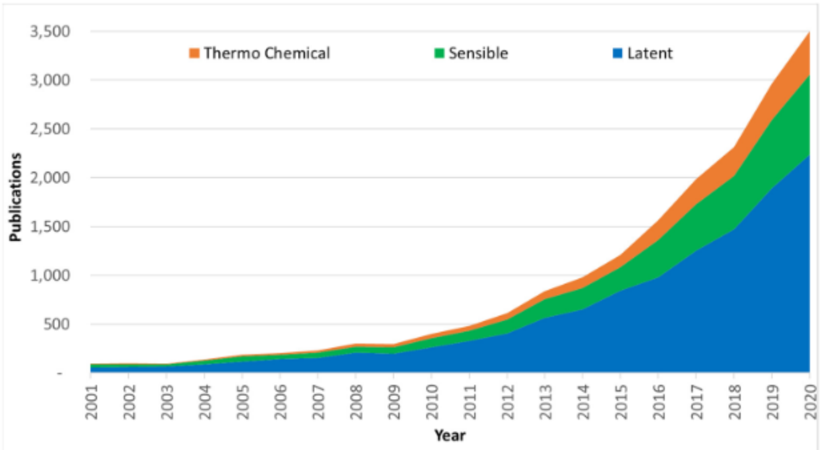

Figure 14: overall publication in the field of heat storage[59]

The area of chemical reaction, or chemical-reversible, has seen massive interest of research in the recent years. Hydrates, carbonates, metal hydrates and redox reactions have been identified as potential heat storage materials. However, no major and promising results were mentioned in previous meta-studies touching thermochemical energy storage.[60] A further and more detailed look into various thermochemical heat

[57] Source: adapted from Sterner, M.; Stadler, I. (2014), p. 537
[58] Cf. Gunasekara, S. N. et al. (2021), p. 11
[59] Source: Gunasekara, S. N. et al. (2021), p. 11
[60] Cf. Gunasekara, S. N. et al. (2021), p. 9

storage materials is made in Figure 15. This thesis focuses on sorption, especially on Adsorption. Salt liquid solutions were the interest of research of previous projects at AEE INTEC.[61]

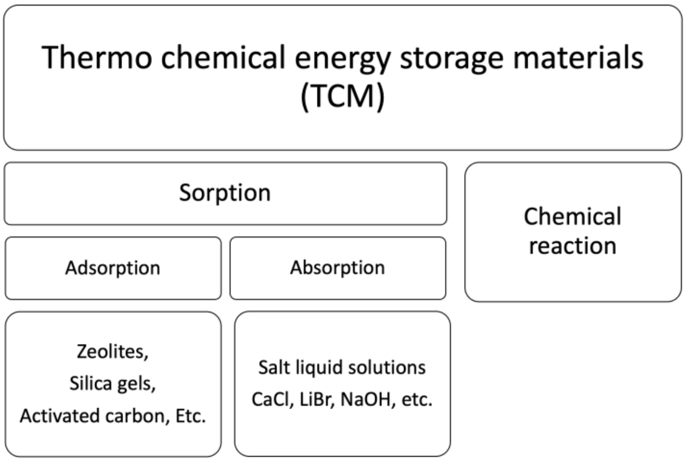

Figure 15: general overview of thermochemical heat storage materials[62]

The focus of this thesis are sorption materials. Common materials in use for adsorption are silica gels, Zeolite and activated carbon. These materials are well known and widely used in other disciplines. Handwarmer, drying pads, air conditioning, air and gas filtration among many others are common applications of sorption materials.[63]

2.1.2 Principles of Sorption heat storage

The fundamental principles of sorption are physisorption and chemisorption. The latter one is a strong bound between the sorbate and the adsorbate, which results in a chemical change of the materials. Common examples of chemisorption are catalyst reactions, where the sorbate enables a reaction of the adsorbate through provision of an alternate reaction path. For the reaction to take place, an activation energy is needed, which results in a minimum temperature to operate.[64]

Physisorption occurs when the force present is mainly the van-der-Waals force. Chemisorption and physisorption are different in terms of the strength of the bound. The bound energy of physisorption is considerably lower. Also, the process of physisorption does not change the chemical structure of neither participants. This results in a reversible process, which can be used for various applications.[65]

The adsorption system in general consists of a working pair of adsorbent and adsorbate. The adsorbent is defined as the material that attracts the free particles, while the free particles are referred to as adsorbate. Based on the characteristics of this pair, different tasks can be carried out, for example heat exchange or heat storage, dehumidification, or pollutant removal.[66]

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[61] Cf. AEE INTEC (2019)
[62] Source: own illustration, adapted from Gunasekara, S. N. et al. (2021), p. 9
[63] Cf. Gunasekara, S. N. et al. (2021), p. 27
[64] Cf. Yu, N. et al. (2013), p. 491
[65] Cf. Yu, N. et al. (2013), p. 491
[66] Cf. Feng, C. et al. (2021), p. 1

Adsorption is a reversible process. During the process of adsorption heat is released, which can then be used. To reverse this exothermal process, heat must be supplied to drive out the adsorbate of the sorbate. This process is called desorption and can be considered a charging process, in which the potential to later produce heat is stored. As the basic idea of energy storage using sorption has now been introduced, the concept will be further developed and described. Through Formula 4 the basic reaction of a sorption process is defined. As shown, sorbate and adsorbate interact on a physical basis and bind together. This releases energy, the binding enthalpy, in the form of heat.[67]

$$\boldsymbol{Sorbate + adsorbate \Leftrightarrow Sorbate \times adsorbate + \Delta H}$$

Formula 4: sorption process[68]

In Formula 5 participants of the sorption process are displayed, where A is the sorbent, B is the sorbate, the combination of A/B is called working pair, m and n are the mole numbers and ∆H (J) is the enthalpy, or the energy available to the user.[69]

$$\boldsymbol{A \times (m + n) + \Delta H \Leftrightarrow A \times mB + nB}$$

Formula 5: general formula for sorption and desorption process[70]

As shown in Figure 16 starting on the top left, the basic cycle of adsorption and desorption can be seen.

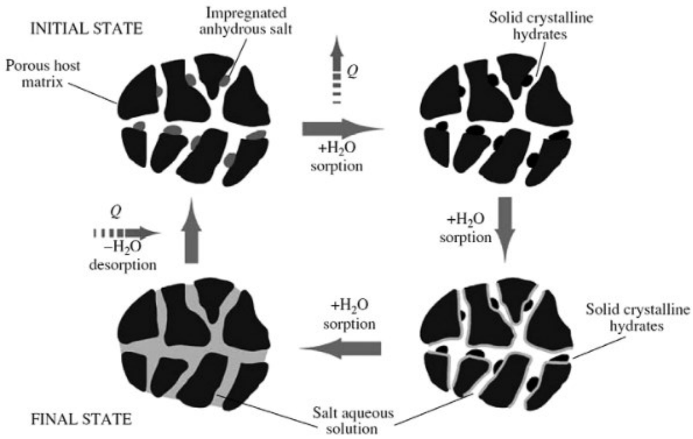

Figure 16: basic cycle of adsorption and desorption in a porous host matrix[71]

Through adsorption of water in the carrier material, where water is complexed on the outside or within the porous matrix, heat is released. This mechanism can be used for cyclical applications. A typical application of this mechanism is air conditioning, especially drying of humid air. However, it can also be used for energy storage applications. This will be described in this section.[72]

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67 Cf. Zeng, Z. et al. (2023), p. 796
68 Source: Zeng, Z. et al. (2023), p. 796
69 Cf. Yu, N. et al. (2013), p. 493
70 Source: Zeng, Z. et al. (2023), p. 796
71 Source: Yu, N. et al. (2013), p. 493
72 Cf. Yu, N. et al. (2013), p. 493

The amount of energy stored through sorption is one interest of this thesis and certainly of most researchers in this field, as it is key for successful deployment. The term Δh_{Ads} ($kJ \cdot kg^{-1}$) describes the differential enthalpy of adsorption, which describes the slope of the isostere in a ln(p)-T-diagram with p as the pressure in Pa and T the temperature in Kelvin. Isosteres are curves of equal loading. More generally, the enthalpy of adsorption is composed of the following enthalpies. Δh_{ads} consists of several components as seen in Formula 6, which indicates, that several parallel processes take place at the same time.[73]

$$\Delta \boldsymbol{h_{ads}} = \Delta \boldsymbol{h_b} + \Delta \boldsymbol{h_v} + \Delta \boldsymbol{h_C}$$

Formula 6: components of adsorption enthalpy[74]

Here, the enthalpy of binding Δh_b is charge dependent, the enthalpy of vaporization Δh_v describes the vapor-liquid phase change, and the configurational enthalpy $\Delta h_C(T)$ is temperature dependent. As the material of choice for various applications can be significantly different, the reactor needs different layouts as well. Sorption materials can range from liquids to powders, rock like solids or extruded and 3D-printed materials. Therefore, several different designs were proposed and tested in recent years. FUMEY ET AL. summarized these concepts and categorized them as shown in Figure 17. A system can either have a fixed bed or a transported bed, where the reaction takes place. At some point the fixed bed reactor needs heating and cooling pipes within the medium, that can transport the energy in and out. Transported bed separates the sorbents, the sorbate, and the combination of both in separate vessels, which means storage tanks and reactor vessels are needed.[75]

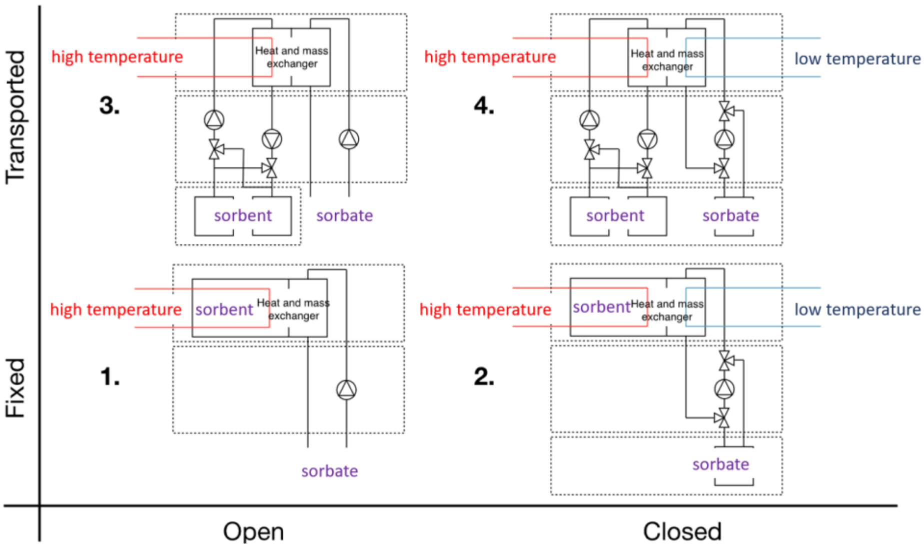

Figure 17: four types of sorption reactors[76]

The other classification, that can be made is based on the working condition of the reactor. The more common approach for sorption technology is to operate under ambient conditions, which is called open system. Often humid air is used as a source of water for

[73] Cf. Meitner, D. (2016), p. 30
[74] Source: Meitner, D. (2016), p. 30
[75] Cf. Fumey, B. et al. (2019), pp. 59–66
[76] Source: adapted from Fumey, B. et al. (2019), p. 59

the sorption process. The other system type operates under vacuum conditions. This enables a distinct view on the sorption process, as no other gases are present. Inert gases, which are problematic, can be avoided through this method. This is explained in Chapter 2.1.5 in detail. In Figure 17 these types of reactors are displayed, where the red lines signal the high-temperature heat source, and the blue lines indicate a heat sink.[77] This thesis focuses on the closed fixed bed reactor with both, heat source and heat sink, and a separate water containment, as presented in the bottom right section of Figure 17.

2.1.3 Choice of sorption material

In prior projects Zeolite 13X has been identified as an adequate and almost optimal material for sorption heat storage applications. In this section the reasoning behind the material choice will be elaborated.[78]

Table 2: parameters used to classify sorption materials[79]

Material Choice Parameters	Unit
density	$kg \cdot m^{-3}$
porosity	$m^3 \cdot m^{-3}$
working pair	-
water uptake	$m^3 \cdot m^{-3}$; $m^3 \cdot kg^{-1}$
regeneration temperature	°C
adsorption temperature	°C
cycle stability	-
thermal conductivity	$W \cdot K^{-1}$
price per unit	$€ \cdot kg^{-1}$
charging power	W
discharging power	W

To find the proper materials for seasonal energy storage, the following parameters, as shown in Table 2, need to be considered and can be essential for successful application. Suitable materials as adsorbate for sorption storage are generally characterized by high porosity. This means that the material has a large inner surface area and can take up a large amount of adsorptive. This directly translates to a high energy density. Other criteria for the material include high power output, low regeneration time, suitable temperature levels, high density, and low investment cost. The most commonly and widely used adsorbent is water, as it is abundant, cheap, and non-hazardous.[80]

In Table 3 an overview over some typical sorbate materials is given, with typical temperature levels, advantages, and disadvantages of the material. Zeolites offer many advantages, while still not being the perfect material. Especially low thermal conductivity poses some technological challenges.[81]

[77] Cf. Fumey, B. et al. (2019), pp. 59–66
[78] Cf. Köll, R. (2015)
[79] Source: own illustration
[80] Cf. Köll, R. (2015)
[81] Cf. Gunasekara, S. N. et al. (2021), p. 22

Table 3: characteristics, advantages, and disadvantages of sorption materials[82]

Material	Typical Temperatures	Advantages	Disadvantages and Challenges
Zeolites	Medium, up to 350°C	Good energy storage density; cheap; good cycle stability	high desorption temperature; low thermal conductivity
Silica gels	Low, up to 90°C	low desorption temperature	low energy storage density; low thermal conductivity
Aluminophosphates	Low, 60 - 90°C	high energy storage density; low desorption temperature; good cycle stability	low thermal conductivity; cost
Metal organic frameworks (MOFs)	Low, up to 90°C	high energy storage density; low desorption temperature; good cycle stability	low thermal conductivity; cost

2.1.4 Zeolites and the working principles

Zeolites are materials composed of crystalline alumina silicates, which are negatively charged and act as a host framework. In total, there are more than 40 different naturally occurring Zeolites, as well as over 150 artificially produced Zeolites. Artificial Zeolites have advantages in terms of density, heat transfer and homogenous consistency. The higher cost of artificial Zeolite is a major disadvantage. Zeolites can be categorized in distinct groups. The most important groups are the type A, type X and type Y. The types differ mainly in the ratio of Silicon to Aluminum which leads to various levels of hydrophilic behavior and resulting in different regeneration temperatures.[83] Also, the size of pores varies to a certain extent. The regeneration temperature is the temperature required to separate sorbent and sorbate, or in other words to charge the storage.[84]

In general Zeolite is a powder-like material. On an industrial scale it can be produced as pellets, granulates, beads, monoliths, or bricks. As the adhesion forces are low, the compressed forms need a binder to stay compressed. This can be achieved through a general binder, which in return uses up some of the space and therefore reduces the density and performance. A binder based on Zeolite can be used too, which is then converted to Zeolite itself. This increases the amount of Zeolite and hence the performance. These Zeolites are called binder free Zeolite (BF).[85]

The Zeolite functions as the adsorbent, the structure which binds free particles. As particles several materials come into play. The combination of the two materials, the adsorbent and the adsorbate, is called a working pair. In preceding studies, going back to the early seventies, many different pairs have been examined and evaluated. The pair of 4A-H_2O and 13X-H_2O have been the most promising ones. In the predecessor project the 13XBF-H_2O pair was chosen, as it has shown in total the most promising performance, mainly since no major disadvantage had to be considered and relative superiority to most other materials was given.[86] In the case of the FlexModul Project this

[82] Source: own illustration, adapted from Gunasekara, S. N. et al. (2021), p. 22
[83] Cf. Aristov, Y. I. (2013), pp. 1610–1618
[84] Cf. Köll, R. (2015), p. 23
[85] Cf. Köll, R. (2015), p. 24
[86] Cf. Köll, R. (2015), p. 24

working pair is Zeolite 13X-water, as 13XBF-H_2O is currently several times more expensive.

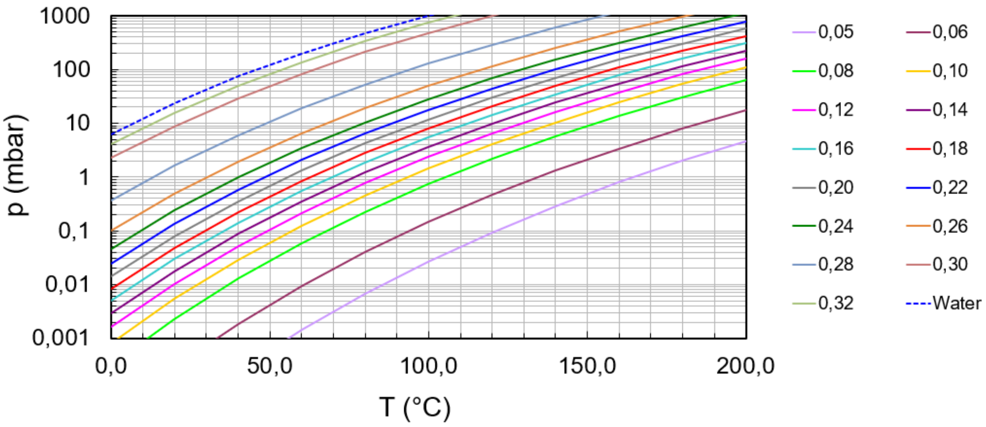

Figure 18: ln(p)-T-Diagram: isosteres of Zeolite 13-XBF[87]

Each working pair can be specified using the isosteres. Isosteres are lines of equal water content. This means that along these lines the mass of water in the Zeolite is constant. Having this information for a material, the loading, or state of charge (SOC), can be retrieved through the known temperature and the pressure. The charging state of a material can therefore be defined or calculated only by measuring either the mass, or temperature and pressure together. When sending steam into the sorption tank at a fully dried state (SOC of 100%) only low pressure is needed and high temperatures are reached. [88] At SOC close to 0%, or the fully wet state, relatively high pressure is needed, or in other words, a lot of water and high temperatures are no longer possible. In Figure 18 the loading curves for the Zeolite 13-XBF-water are shown in an ln(p)-T-Diagram, the isostere diagram. On the x-axis the temperature of the state is given, while on the y-axis the logarithmic pressure is shown. The various colors in the diagram show the mass fraction, ranging from 0% to 33%, or in other words the SOC between 0% and 100%.[89]

2.1.5 Problems and improvement in sorption technology

In the field of sorption many different problems can occur, that are unknown in other areas of energy storage. Zeolite, for example, adsorbs not only water vapor but also inert gases. This can take place during the production process or when filling the tank. Therefore, it is difficult to prevent inert gas from occurring around Zeolite. In general, an inert gas is a gas that rarely reacts with other components. Nitrogen, carbon dioxide, and noble gases are examples of inert gases. They must be removed to have a reliable adsorption and desorption process. They cause several different problems, including disturbed measurements caused by increased partial pressure. In the case of FlexModul no mechanical equipment is necessary to transport water vapor. Transport occurs only due to pressure differences. The inert gases, however, increase the pressure in the vessel and therefore decrease the pressure difference, which is the driving force of

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[87] Source: own illustration
[88] Cf. Köll, R. (2015), p. 48
[89] Cf. Köll, R. (2015), p. 48

FlexModul. To prevent inert gases, the vacuum, under which FlexModul operates, needs to be renewed in regular intervals at the beginning of the operation, as inert gases slowly diffuse out of water and the sorption material.[90]

Improvements in sorption materials and TCM can be achieved through various processes, including impregnation with salts or the coating of the material with a water repellent material. Both methods have shown very promising results. MEITNER concluded that composite materials for use in TCS are not ideal, and that more research is needed into ion exchange and hydrophobization. The main advantage of hydrophobization can be the improved stability and durability of salt impregnated materials, as well as the improved energy density. Long-term stability is yet to be proven.[91, 92, 93, 94]

2.2 Interest of research

The interest in research has been steadily increasing over the past 20 years. In general, the number of publications around thermal energy storage has quintupled. In Figure 19 it can be seen that interest in this area is picking up. A similar picture can be seen in the areas of sorption heat storage and Zeolite heat storage as well. A very high interest in Zeolite can be seen. Improvements on the material side of thermochemical energy storages are expected due to the high interest.

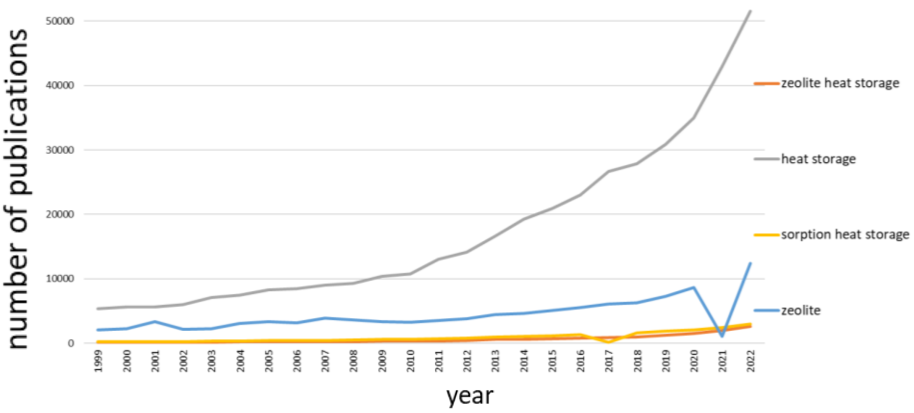

Figure 19: interest and current research[95]

2.3 KPIs: comparing energy storage technologies

The project FlexModul aims to bring sorption technology to market readiness.[96] For this target to be achieved, the business side needs to be investigated in detail. In this section

[90] Cf. Köll, R. (2015), p. 51
[91] Cf. Köll, R. (2015), p. 28
[92] Cf. Meitner, D. (2016), p. 4
[93] Cf. Meitner, D. (2016), p. 101
[94] Cf. Feng, C. et al. (2021), p. 10
[95] Source: own illustration based on data from: https://www.sciencedirect.com
[96] Cf. AEE INTEC (2019)

the most relevant economic basics will be discussed. Also, basic ideas for modelling the use cases against which sorption storage will be measured will be illustrated. To compare various storage technologies, a set of performance indicators (PI) needs to be defined. Some basic of business and economics need to be elaborated as the basis for the financial performance indicators. The financial and technical set of indicators is described in this section and is based on an extensive literature review.

2.3.1 Business and economic basics

In this section the fundamental basics for a business economic analysis relevant to FlexModul will be discussed.

The net present value method assesses investment alternatives in relation to a monetary target. The net present value (NPV) is the sum of all inflows and outflows, also called net cashflow R_t (€), discounted or compounded to a point in time t (year or month) with the interest rate i (%).[97]

The NPV model assumes the existence of a perfect capital market. The uniform interest rate available on this market, at which financial resources can be invested or borrowed in any amount, is used to compound, or discount payments. The net present value is often related to the beginning of the planning period, i.e., the time immediately before the first payments. This is also assumed in the following. The net present value is then the sum of all payments discounted to this point in time that are affected by an investment object. In this case, it represents a present value, which can be interpreted as the increase in financial assets that the investment object generates at the beginning of the planning period, taking interest into account. When the net present value method is applied, the following benefit rules apply to investment objects.[98]

An investment object is absolutely advantageous if its net present value is greater than zero. An investment object is relatively advantageous if its net present value is greater than that of any other object available.[99]

$$NPV = \sum_{t=0}^{t} \frac{R_t}{(1+i)^t}$$

Formula 7: net present value (NPV)[100]

The annuity method is based on a model that corresponds to the net present value method. The model is merely evaluated regarding a different target value, the annuity. An annuity is a sequence of equal payments that accrue in each period of the period under consideration. It can be interpreted as the additional amount that an investor can withdraw in each period if a project is carried out. The annuity of an investment object is equivalent to the capital value of the same object. The following criteria of advantageousness apply to the annuity method: An investment object is absolutely

[97] Cf. Götze, U. (2014), p. 78 ff.
[98] Cf. Götze, U. (2014), p. 78 ff.
[99] Cf. Götze, U. (2014), p. 78 ff.
[100] Source: Probasco, J., https://www.businessinsider.com/personal-finance/npv (Retrieved: 16.03.2023)

advantageous if its annuity is greater than zero. An investment object is relatively advantageous if its annuity is greater than that of any other object available for selection. When calculating the annuity, the payments of the payment sequence are usually related to the end of the period. This is also assumed in the following. The useful life of the object is initially selected as the period under consideration. The annuity of an investment object can be calculated by multiplying the (NPV) of the object by the recovery factor. This depends on the discount rate i (%) and the useful life t.[101] The annuity is calculated as:

$$Annuity = NPV \times \frac{i \times (1+i)^n}{(1+i)^n - 1}$$

Formula 8: annuity method[102]

Capital expenditures (CAPEX) comprise all longer-term investments in the assets of a company. The aim of capital expenditures is to increase production and productivity to boost sales and profits. Typical capital expenditures include investments in machinery, buildings, and initial equipment such as office furniture. CAPEX are usually one-time payments made in advance. As an investment in fixed assets, they increase the asset side of the balance sheet. The assets are used and depreciated over a period of several years.[103]

Operational Expenditures (OPEX) include all expenses that are necessary to enable and continuously ensure a functioning operational business. What constitutes operational expenses also varies from company to company. Typically, operational expenses include the cost of raw materials and supplies, personnel costs, energy costs, and selling and administrative costs. Operating expenses are recurring expenses that are usually paid monthly or annually.[104]

In the world of finance and energy, there are several ways to calculate the cost of a product or a service. For the production side the levelized cost of energy (LCOE) has gained immense importance to compare several types of energy sources. The concept of LCOE is the basis for the prices on the electricity market and the merit order. LCOE in $€ \cdot kWh^{-1}$ is defined as follows. The total cost of an investment over its lifetime divided by the sum of the overall produced energy by the investment. It can also be defined by the NPV, where the LCOE becomes the average price at which energy can be sold to achieve a zero NPV. This is a slight difference in the definition, however, not having a consequence on the formula or the result. In Formula 9 I_0 is defined as the initial investment in €, A_t as the annual cost of operation in €, $M_{t,el}$ the produced amount of energy per year in kWh, t the lifetime since the start in years and n the total economic lifetime.[105]

[101] Cf. Götze, U. (2014), p. 100 pp.
[102] Source: Götze, U. (2014), p. 100 pp.
[103] Cf. Ross, J., https://www.investopedia.com/ask/answers/112814/whats-difference-between-capital-expenditures-capex-and-operational-expenditures-opex.asp (Retrieved: 17.03.2023)
[104] Cf. Ross, J., https://www.investopedia.com/ask/answers/112814/whats-difference-between-capital-expenditures-capex-and-operational-expenditures-opex.asp (Retrieved: 17.03.2023)
[105] Cf. Kost, C. et al. (2018), p. 29

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

Formula 9: levelized cost of energy (LCOE)[106]

The project lifetime is crucial for the result. An average life span of 25 years is usually assumed.[107,108] In a system where most of the generation is ensured by flexible thermal units, LCOE is a meaningful criterion as the integration of wind and solar does not trigger massive adaptation of the system to accommodate their variability.[109] LCOE is important for the following concepts, however, it will not be used for FlexModul.

The merit order principle is the basis for European electricity prices. Power capacities are ordered according to their LCOE, hence the name merit order. This leads to an optimal production capacity. Plants with low production costs can run cheaply and are used for base load applications. Higher prices and hence higher LCOE are paid, if necessary, especially during peak demand and contribute to the stability of the grid. This is the case for gas plants. In some countries the highest priced capacities are oil and oil products, which are only used in extreme conditions. Under normal market conditions the price relates to the current demand. As can be seen in Figure 20 on the left, where a slow and steady ramp defines the prices. Only in the highest demand scenarios steep ramps do occur. In 2022 some extreme scenarios were seen, where natural gas prices rose to unprecedented levels and led to the sharpest and steepest ramp of a merit order in Germany ever, as demonstrated in Figure 20 on the right.[110]

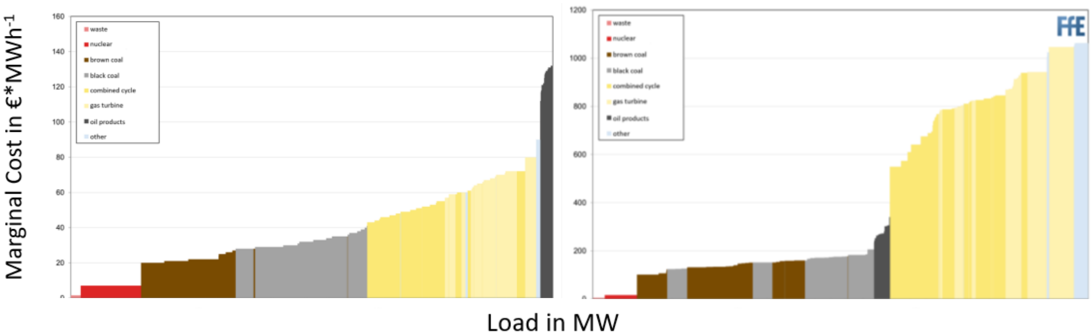

Figure 20: merit order of thermal power plants, Germany 2018 vs. Germany 2022[111]

The concept of levelized cost of storage (LCOS) provides an objective and transparent method for comparing cost and performance for different energy storage technologies. LCOS defines operational parameters associated with energy storage systems, aggregates cost and operational data, analyzes, based on the installed cost, what revenue is needed over the indicated project life to achieve certain levelized returns for

106 Source: Kost, C. et al. (2018), p. 29
107 Cf. Pawel, I. (2014), p. 69
108 Cf. Kost, C. et al. (2018), p. 29
109 Cf. Kättlitz, A et al. (2022), p. 56
110 Cf. Ganz, K. et al., https://www.ffe.de/veroeffentlichungen/veraenderungen-der-merit-order-und-deren-auswirkungen-auf-den-strompreis/ (Retrieved: 22.12.2022)
111 Source: Ganz, K. et al., https://www.ffe.de/veroeffentlichungen/veraenderungen-der-merit-order-und-deren-auswirkungen-auf-den-strompreis/ (Retrieved: 22.12.2022)

various technologies and provides the basis for direct comparison among various technologies within a selected subset of found use cases. CAPEX is added to the annual cost at each point of time t over the lifetime of the storage system, discounted with the interest rate i in %. The LCOS method has been described by the author previously for battery storage systems and has been widely used since.[112, 113] LCOS describes under the assumption of a NPV of zero, which minimum revenue is required for each unit of usable energy.[114]

$$LCOS = \frac{\sum(CAPEX + OPEX) \times (1+i)^{-n}}{\sum E_{discharge} \times (1+i)^{-n}}$$

Formula 10: levelized cost of storage (LCOS)[115, 116]

In Table 4 the latest LCOS numbers are presented for various market participants based on the yearly energy output. Prices behind the meter for end consumers are significantly higher than in front of the meter. However, a significant benefit can be seen when employing photovoltaic systems. As shown Table 4 the acceptable prices of storage capacity are higher in residential use and decrease significantly in industrial applications. For storage system on grid scale the acceptable prices are significantly lower.[117]

Table 4: LCOS analysis by Lazard, cost per unit stored[118]

	capacity		power	
	lower limit $\$\cdot MWh^{-1}$	upper limit	lower limit $\$\cdot kW^{-1}$	upper limit
Commercial & industrial (Standalone) 1 MW; 2 MWh	442	643	221	318
Commercial & industrial (PV + Storage) 0,5 MW; 2 MWh	235	335	378	521
Residential (PV + Storage) 0,006 MW; 0,025 MWh	415	621	545	785

The concept of levelized cost of heat (LCOH) is analogous to LCOS and LCOE. As shown in Formula 11, LCOH can be calculated by adapting the LCOE concept to heat production. This is with CAPEX as the initial investment, i as the real discount rate, and E_t as annual heat production. OPEX includes operation and maintenance costs, including fuel costs.[119]

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[112] Cf. Wilson, M. (2017), pp. 1, 3, 6
[113] Cf. Jülch, V. (2016), p. 1598
[114] Cf. Schmidt, O., https://www.storage-lab.com/levelized-cost-of-storage (Retrieved: 04.04.2023)
[115] Source: Belderbos, A. et al. , p. 1
[116] Source: adapted from: Xu, Y. et al. (2022), p. 7
[117] Cf. Lazard Ltd., http://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/ (Retrieved: 16.03.2023)
[118] Source: own illustration, adapted from: Lazard Ltd., http://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/ (Retrieved: 16.03.2023)
[119] Cf. Yang, T. et al. (2021), p. 3

$$LCOH = \frac{CAPEX + \sum_{t=0}^{n} \frac{OPEX}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

Formula 11: levelized cost of heat (LCOH)[120]

2.3.2 Technical Performance indicators

To be able to compare distinct types of TES or energy storages in general, parameters and characteristics need to be defined. The major distinction between the parameters is if they are power or energy related. DEL PERO ET. AL defined their KPIs as follows. Their focus was mainly on building and housing applications. This lays the foundation for the FlexModul PIs, as the field is relatively similar. Power related characteristics are mainly related to charging and discharging. Especially the charging power P_{char} (W) and the discharging power P_{dis} (W) are important for consideration. Also, power density has a particularly significant role, as space almost always is a critical factor. The power gradient is especially important for dynamic use of energy storage and is a measure for changing power out- or input of the system. Commonly used for battery systems is the c-rate. The c-rate is defined as the time in which the storage can be fully charged or discharged. Capacities are usually given at a c-rate of 1.[121,122] Energy related characteristics are related to the actual amount of energy stored. The total energy E or Work W (Wh, J) and the energy density either related to Volume or related to mass. The charging power of an energy storage P_{char} (W) is defined as the difference of energy input W_{in} (W) over time t. The same is true for discharging power P_{dis} (W) in relation to change in discharged energy W_{out} (W).[123] Both terms are demonstrated in Formula 12 and Formula 13.

$$\boldsymbol{P_{char} = P_{in} = \frac{dW_{in}}{dt} = \frac{W_{in}}{t_{in}}}$$

Formula 12: charging power[124]

$$\boldsymbol{P_{dis} = P_{out} = \frac{dW_{out}}{dt} = \frac{W_{out}}{t_{out}}}$$

Formula 13: discharging power[125]

One important factor for energy storage in general is the change of power input and power output. This characteristic is called the power gradient (PG) and is defined as the change of power in or output over time, as illustrated in Formula 14. A high PG enables fast changes of input or output, which again enables fast levelling of supply and demand. This is necessary for stable operation. [126]

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[120] Source: Yang, T. et al. (2021), p. 3
[121] Cf. Spendiff-Smith, M., https://www.power-sonic.com/blog/what-is-a-battery-c-rating/ (Retrieved: 16.03.2023)
[122] Cf. Del Pero, C. et al. (2018), p. 63
[123] Cf. Sterner, M.; Stadler, I. (2014), p. 38
[124] Source: Sterner, M.; Stadler, I. (2014), p. 38
[125] Source: Sterner, M.; Stadler, I. (2014), p. 38
[126] Cf. Sterner, M.; Stadler, I. (2014), p. 39

$$PG = \frac{dP}{dt} \; with \; P = P_{in} = P_{out}$$

Formula 14: power gradient[127]

However, transformation, transport and storage of energy are always associated with losses. Therefore, a storage efficiency η_{stor} needs to be introduced, as in Formula 15, alongside the charging efficiency η_{in} and the discharging efficiency η_{out}. An important characteristic of energy storage is its round-trip efficiency (RTE). Usually, the efficiency is defined as usable energy W_{out} versus deployed energy W_{in}.[128]

$$\eta_{total,ideal} = \frac{W_{out}}{W_{in}} = \eta_{in} \times \eta_{out}$$

Formula 15: ideal total efficiency[129]

$$\eta_{total,real} = \frac{W_{out}}{W_{in}} \times \left(1 - \frac{W_{loss}}{W_{stor}}\right) = \eta_{in} \times \eta_{stor} \times \eta_{out} = RTE$$

Formula 16: real total efficiency[130]

The roundtrip efficiency (RTE), however is defined as the amount of energy available divided by the amount of energy that was stored in the system, as shown in Formula 16. It is equal to the real efficiency of the system $\eta_{total,\,real}$.[131]

For performance comparison the operating temperature is very important, as it defines and limits the area, in which the storage technology can be used, or at which temperature the storage can be discharged. As a storage needs to be charged as well, the charging temperature is also important, as it usually is significantly higher than the usable temperature. This defines a certain frame for energy sources. PALOMBA AND FRAZZICA tried to define a KPI set, for comparison in the field of thermal energy storage. The defined KPIs and the results are displayed in Table 12. Based on this proposed KPI set, the further comparisons will be conducted.[132]

2.3.3 Financial Performance Indicators

Primarily, FlexModul needs to be competitive on its own and on a system level. Other storage technologies as for example battery electric storage systems, sensible heat storages (SHS) and latent heat storage (LHS) are technologies, against which FlexModul can be measured against. Even though the technologies are significantly different, FlexModul still needs to be competitive from a financial standpoint to be successfully marketed. An economic benefit or a use case no other technology can deliver, needs to be present. The unique selling proposition or unique selling point (USP) in any case is the long-term aspect of storage, without any storage losses at all. As demonstrated later in sections 3 and 4.2.1, all losses occur during the charging and discharging process.

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[127] Source: Sterner, M.; Stadler, I. (2014), p. 39
[128] Cf. Sterner, M.; Stadler, I. (2014), p. 38 pp.
[129] Source: Sterner, M.; Stadler, I. (2014), p. 40
[130] Source: Sterner, M.; Stadler, I. (2014), p. 40
[131] Cf. Sterner, M.; Stadler, I. (2014), p. 38 pp.
[132] Cf. Palomba, V.; Frazzica, A. (2019), p. 97

This USP can, however, be hardly measured from a financial standpoint. Therefore, the financial framework needs to perform well.

Secondly, for economic and technological optimization, a lot of distinct factors need to be considered. The most challenging decision for this project certainly is the material choice. As of 2023, many material tests have been conducted at AEE INTEC in Gleisdorf. For reference tests Zeolite 13X and Zeolite 13XBF have been used, as stability and performance were at an optimum at the local tests. In 2019 PALOMBA AND FRAZZICA published an extensive review of performance indicators, energy-related PIs, and at last KPIs for the field of energy storage. The further KPIs will all be based on this work. In the past, the main research on KPIs on sorption energy storage systems was mainly carried out by the groups around AGHEMO, PALOMBA, and DEL PERO. Based on their past publications a vast pool of KPIs was available, which was then reduced to the essentials. These KPIs are then used to measure the performance of FlexModul. The overview with the results is given in Table 12.

3 Preparation for Practical Work

The following section will describe the plant in detail, including the setup, the working principles of the components, and the energy flows in each operating state. This setup was designed to carry out component tests and it is almost identical to the system, that will be deployed in the field. Some parts, however, will be different due to local conditions. The business cases will be described and elaborated.

3.1 Components of the plant

First, it needs to be noted that the system is sealed and operates under vacuum at an absolute pressure of 1 to 50 millibar (mbar). Therefore, significant emphasis is laid on the components themselves. Few standard components are usable for the reactors or the evaporator and condenser. This is due to the low pressure and the high forces acting on each unit due to the surrounding pressure.

The plant layout is demonstrated in Figure 21 and will be discussed in detail.

The primary component of the plant is the prismatic tank, where energy is stored. It consists of a heat exchanger with a bed of Zeolite, the sorption material, embedded. Zeolite has bad thermal conductivity, comparable to thermal insulators. Therefore, a very high contact area is needed between the material and the heat exchanger. The tank has one connection to the steam channel, which is used in both directions. Two more heating connections connect the external heating system to the internal heat exchanger in the tank. Several prismatic tanks can be deployed together. They only need to be connected to the steam channel and the heating system. The storage tank itself needs to withstand pressures down to 5 mbar. So, the heat exchanger and the material within help the surrounding steel structure withstand the pressure difference.

On the supply side, a high-temperature and a low-temperature heat source are needed. High temperatures are generated through a heating rod, which generates up to 200 °C. To prevent steam formation, thermo-oil is used as a heat transfer fluid (HTF). This operating medium for the heat supply can withstand up to 380 °C before evaporating. An HTF pump at high temperatures is used to transfer heat into and out of the storage tank.

A further heat exchanger is connected to the HTF cycle to supply heat to the conventional heating system of the house, which is based on water.

A key component of the system is the evaporator and condenser (EC), which is one part and functions in two distinct ways. It evaporates water at very low pressure and temperature, transfers the water from the water tank to the sorption tank and retrieves energy. The EC also acts as a condenser when the sorption tank is heated up and the water is driven out. The low-temperature heat for evaporation below 20 °C is supplied by a domestic water heat pump (DWHP). The steam that is released through charging the sorption tank can also be retrieved through the condenser at the desired temperature level. This steam can be used in domestic hot water (DHW) and heating applications.

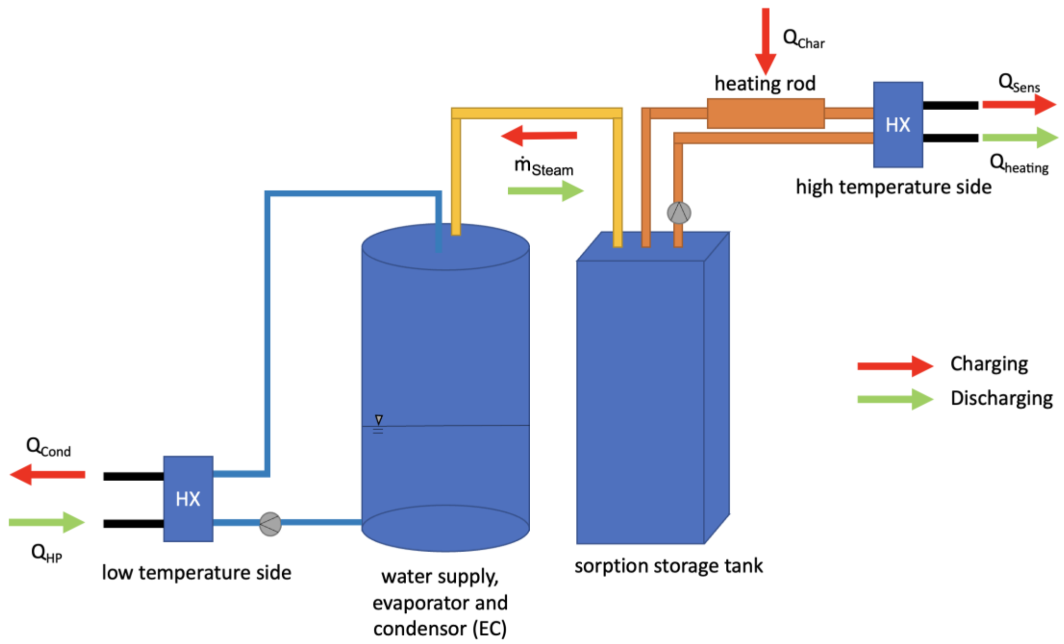

Figure 21: plant setup of FlexModul[133]

For the system to function, many connections are needed. This is demonstrated in Figure 21. First, the steam channel from the EC to the sorption tank, is highlighted in yellow. This channel transfers steam in both directions depending on the relative pressures in the two tanks and therefore on the operating mode. Second, the storage tank is connected to the HTF cycle for heating purposes, as shown in the orange box. A heating rod is deployed in this cycle, to potentially heat up the HTF. Thirdly, the interconnection between the low-temperature heat source and the EC for low energy heat supply, highlighted in light blue. Lastly, the connection of the EC and low-temperature heat source to the house heating system, shown as black interconnections. The two states of operation, that will be discussed in the section 3.2, are shown in red and green. Red indicates the charging process, where energy is put into the system through a heating rod. Heat can be used as condensation heat Q_{Cond}, displayed on the left and the sensible heat Q_{sens} on the right. The inverse discharging process is displayed in green, where auxiliary energy is supplied through a HP. This starts the process and supplies the desired heating energy $Q_{heating}$ on the right.

In the system two pumps are needed. One pump must withstand high temperatures and be able to pump the corrosive HTF. It is used to heat up the system with a heating rod. The second pump is a conventional water pump for home-applications with no specific requirements, except vacuum tightness.

For this complex system to function properly, many measurements are necessary. First, several temperature sensors across all parts of the plant need to be deployed. Also, pressure sensors on the EC side and for each sorption tank are necessary to calculate the charging state. Through these measurements, stored energy, energy flow and various performance metrics can be measured. To verify those measurements, weight and flow measurements are used in the test plant.

[133] Source: own Illustration

To scale up the system, several storage tanks can be connected in series. This will be done in the case of the field tests. To function properly, the high-temperature side as well as the steam channel need to be connected.

3.2 Charging and Discharging Process

Compared to sensible heat storages, where energy is stored as sensible heat, also known as heat, In FlexModul, a concept which is more like a battery is used. The energy is not stored in the form of heat. The energy is stored in the potential to generate sensible heat, like energy in a battery is stored in the potential to react and supply electricity. Therefore, the charging process consists of several steps, as demonstrated in Figure 23 and Figure 22. The charging is achieved through heating up the system, shown in Figure 22 as Q_{char} (kWh). For low temperatures this can be achieved through thermal solar power or a heating rod. To fully dry up the system and hence to fully charge it, temperatures up to 180 °C are needed, which can only be reached with a heating or vacuum solar collectors. During this heating process, a constant stream of water steam is driven out of the storage and then condensed in the EC, which constantly needs to be cooled through using the energy Q_{cond} (kWh) for DHW applications to enable a continuous process. The evaporation heat can be used for DHW and heating. The condensed water is stored in a separate storage tank for later use.

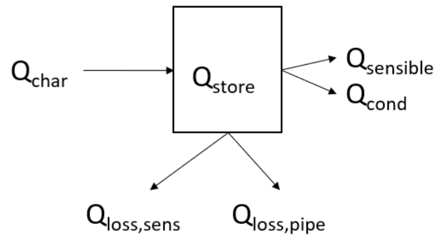

Figure 22: energy flow during charging process[134]

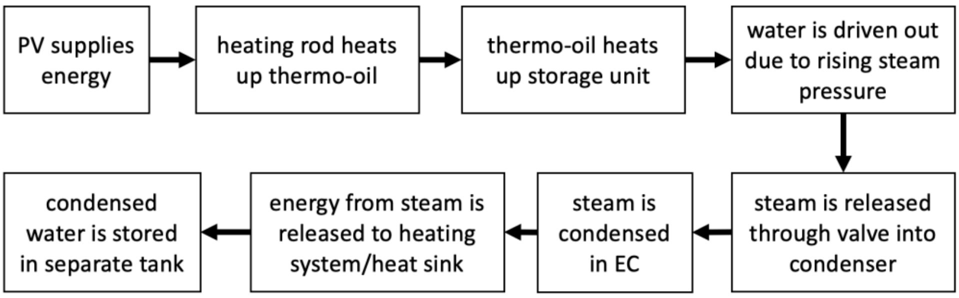

Figure 23: charging process scheme[135]

In the fully charged state the sorption material is dry and has a temperature of around 180 °C, depending on the preceding charging process. This energy in the form of heat can be used immediately to supply DHW or to charge other units of FlexModul. If used, this energy is identified in Figure 22 as $Q_{sensible}$ (kWh). If the energy cannot be used, the

[134] Source: own illustration
[135] Source: own illustration

heat is lost and shown as $Q_{loss,sens}$ (kWh). Energy also dissipates through the piping as $Q_{loss,pipe}$ (kWh). The stored energy through sorption is not dependent on the use of the heat. However, if not used, the efficiency of the charging process is significantly lower. The key to successfully operate the sorption storage is to wisely manage the losses. In the process of charging, due to the transfer of masses, energy is also moved out of the system at a temperature level, where it cannot be retransferred to the system. Therefore, this energy needs to be used and can be utilized for DHW. Sensible heat losses occur during charging and discharging. Especially, the heat, that is left in the storage tank after charging can make a significant difference and therefore needs to be used. So, energy is stored within the system as potential to generate heat for long time storage as well as in sensible heat of the system for short term storage. The stored heat is shown as Q_{store} (kWh).

The discharging process is used to supply heat for DHW and heating. To release energy from the sorption storage, low-level heat needs to be delivered to the EC to evaporate water at low temperatures, as demonstrated in Figure 24 and Figure 25. This is achieved through a minimum temperature in the DWHP and demonstrated as Q_{HP} (W). As the steam migrates to the sorption storage, it adsorbs onto the sorption material and releases heat. This heat is then retrieved though the embedded heat exchanger and delivered through the HTF cycle to the heating applications. A constant supply of fresh low-temperature steam is supplied by the DWHP and the EC.

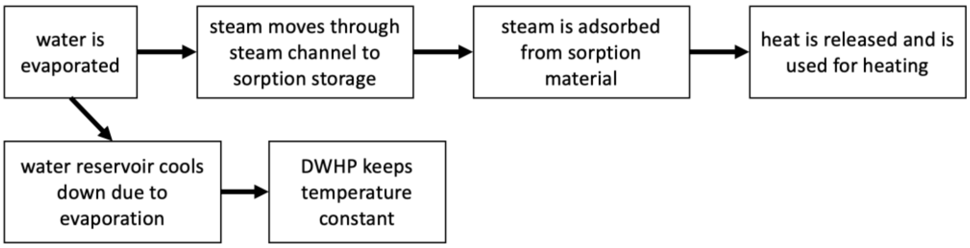

Figure 24: discharging process[136]

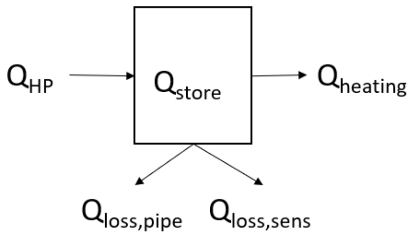

Figure 25: energy flow during discharging process[137]

In Figure 26 the charging and discharging process combined with all energy flows is displayed. For adequate use of the system, it is essential to highlight, that the process of charging is connected to high energy losses, which needs to be actively managed. Waste heat can and needs to be used. If it is wasted, the overall efficiency is significantly lower, and the system becomes unattractive from a technical and economic point of view.

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[136] Source: own illustration
[137] Source: own illustration

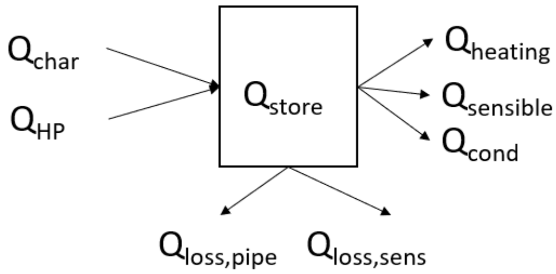

Figure 26: energy flow of the whole process[138]

3.3 Description of Business Cases

In this thesis two distinct business cases will be investigated.

The first business case explores the potential to store energy seasonally. Spring and summer surplus energy is conserved. Throughout the year, especially in fall and winter, when available energy is low and heating demand rises, stored energy is used.

The second business case uses electric grid energy. As large amounts of wind parks and PV arrays are being constructed the energy supply is expected to become more volatile. Flexibility is provided through active management of electric grid demand. Through a heating rod, surplus energy can be stored for later use. Business Case 2 assumes that this service can generate income through premiums, as in industrial applications. The basis for this business case will be EAG's work, which currently develops products around flexibility for consumers. Forecasts by energy and utility companies for demand for this service in unison with day-ahead prices will lay the foundation for implementation and decision making.

A combination of the two business cases will be investigated if it can be determined that both are viable.

[138] Source: own illustration

4 Practical Work: Market Analysis, Simulation and Analysis of Results

This section describes the practical aspects of the project and the financial and economic analysis. There will be a comparison and analysis of the results. In the practical part of the study, the plant underwent extensive and thorough testing. The system is explained in detail first. A thorough technical and financial analysis was conducted based on system data. This analysis was used to calculate financial costs. Cost estimations were done top down and bottom up. This led to the setup and calculation of a DCF model. Finally, the results were analyzed and presented.

4.1 Market analysis and market review

To properly set up a use case that can be relied on for further calculations, a thorough analysis of the status quo is needed. Considering the differences in needs between households, service sectors, and industries, a detailed look is needed. Heating and cooling in terms of room heating are similar in all instances while the maximum temperature is quite different.

In this section, a thorough analysis of the data will lay the basis for various use cases. These will be used as a benchmark for sorption heat storage systems. They will also be used to validate or falsify economic assumptions in this project. The key questions discussed in this section are:

- How does the current market look like? What technologies are currently leading the market?
- What trends in terms of heating methods are present?
- What are customers willing to pay?
- Are customers willing to invest in upgrades and new technologies?
- What use cases can be deducted?

4.1.1 Status-quo of heating in households

For realistic development of reference use cases, a look at the status quo is needed. To find proper references, where FlexModul can be measured against, a data basis is needed. As an example, Statistik Austria datasets were used. As shown in Figure 27, a major share of heating in Austria is based on renewable energy sources. As electricity production has a share of over 70% in renewable production and district heating has a share of slightly below 50% in renewables, the total share of renewables is even higher.

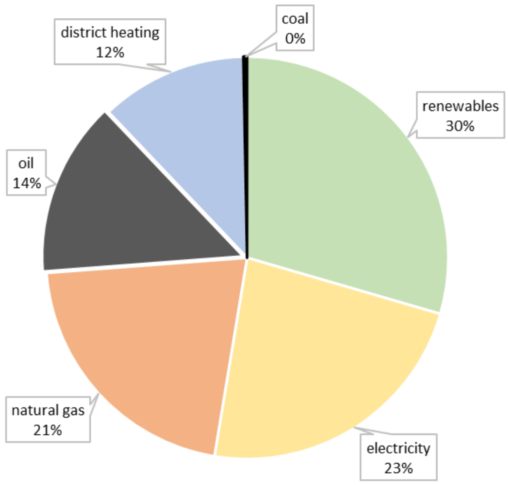

Figure 27: sources of energy for heating in 2019/2020 in Austria[139]

Currently, there are many changes taking place in the field of heating, as can be seen in Table 5. On the carbon intensive side, a massive reduction in both coal and oil-powered heating systems can be seen, -86,2% and -44,1% respectively. Low gains for wood and wood-related materials +14,1%, natural gas +4,4% and low losses for electricity-powered heating (power to heat) with -0,5% were observed. The largest changes can be found on the district heating side with a solid doubling of users. However, it is not evident from the data whether the supply systems are carbon neutral, or carbon-based. Solar and HPs have the highest gain with over 300% gain. Based on this dataset, the most promising comparisons are wood, electricity, natural gas, solar and heat pumps, and district heating.[140]

Table 5: total number of heating systems in Austria, 2003 vs. 2019[141]

	2003/2004	2019/2020	Change [%]
Wood, pellets, wood chips	584 977	667 354	14,1%
Coal, coke, briquetts	59 782	8 255	**-86,2%**
Oil, LPG	910 812	508 861	**-44,1%**
Electricity	252 418	251 243	-0,5%
Natural Gas	871 995	910 736	4,4%
Solar, Heat Pump	103 602	421 385	**306,7%**
District Heating	591 687	1 196 292	**102,2%**
Total	**3 375 273**	3 964 126	**17,4%**

Understanding current developments requires year-over-year comparisons (YOY). In Figure 28 it can be seen that electric heating is stagnating in the range of +/- 2% YOY. In contrast, solar and HP, despite falling in the first years of observation, have revived. In recent years, their popularity has grown even stronger.[142]

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139 Source: adapted from Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)
140 Cf. Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)
141 Source of data: Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)
142 Cf. Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)

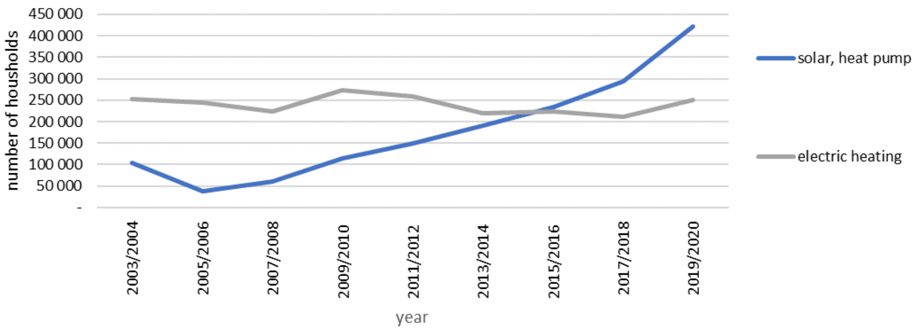

Figure 28: comparison of the solar/heat pump vs. electricity heating[143]

For further comparison, a look at the network-based heating sources, natural gas and district heating is needed, as both have extremely high installation costs in terms of network access in common. As shown in Figure 29 district heating has risen to the top of the market and is the single largest source of heating in Austria. Natural gas heating has been stable over 20 years. This can be largely attributed to natural gas friendly policies and grid expansion in the late 1990s and early 2000s in Austria. [144]

Based on these figures, a clear reference for FlexModul can be derived. Two distinct approaches are used to select use cases. For redevelopment and renovation, Gas, District Heating, Electric Heating, HP, and Solar are technically the best options. District heating, electric heating, heat pumps, and solar are the references for all updated systems and new developments. The main difference between these use cases is if infrastructure is available, such as gas pipes or district heating pipes.

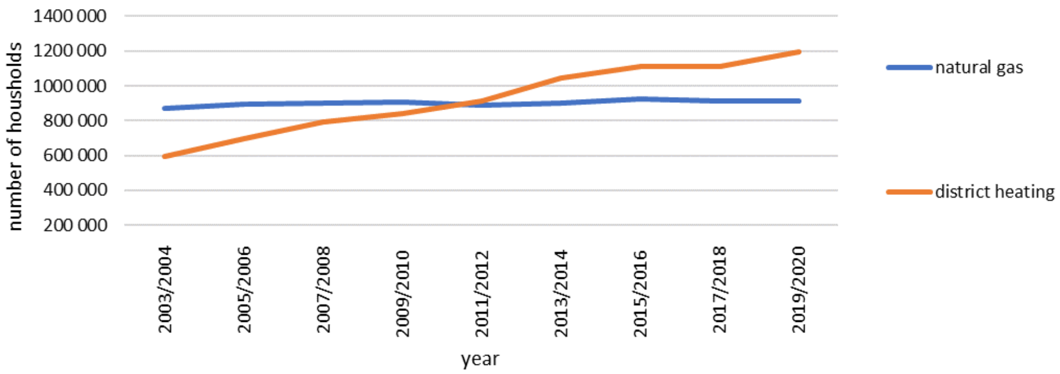

Figure 29: natural gas vs district heating[145]

As shown in Figure 30 it becomes clear where the major share of energy is used. Space heating in single family homes (SFH) and multifamily homes (MFH) are a major share of the total heat consumption of the residential sector. Addressing the need for heat and shifting the load from winter to summer can achieve massive results. A TES can therefore be assumed effective when tackling gas, oil, coal, and electricity as heating

143 Source: own illustration, Data source: Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)
144 Cf. Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)
145 Source: own illustration, Data source: Statistik Austria, https://www.statistik.at/statistiken/energie-und-umwelt/energie/energieeinsatz-der-haushalte (Retrieved: 30.11.2022)

methods and to assist and substitute them through using surplus energy from summer months in space heating application.

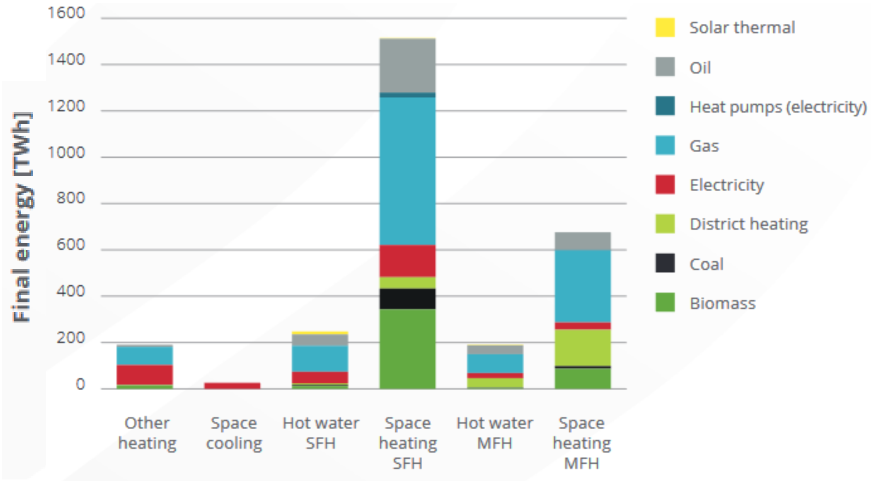

Figure 30: residential sector by single/multi-family house in 2015 (EU28)[146]

In terms of houses and apartments, Europe's situation is vastly different. In Spain on the one hand, 66% live in apartments and around 15% in single family homes. On the other hand, in Croatia only 21.7% live in apartments and almost 70% in single family homes. Poland, Bulgaria, Slovakia, Austria, Sweden, and Denmark are all almost split. To sum up, no clear trend based on geographical region is present.[147]

4.1.1 Residential energy prices

In addition to energy consumption, energy prices are a major factor. As the prices have increased substantially over Europe in the years 2021 and 2022 new scenarios need to be considered. As shown in Figure 31 the prices rose dramatically more than their long-time average. Price hikes of up to 60% were seen in countries like Czechia, Latvia, or Denmark, while Slovenia and Netherlands saw dramatic decreases in their prices. This was caused by governmental subsidies to lower the energy prices and counteract the financial burden for the population.[148]

[146] Source: Heat Map Europe, https://heatroadmap.eu/wp-content/uploads/2019/03/Brochure_Heating-and-Cooling_web.pdf (Retrieved: 19.12.2022)
[147] Cf. DE Statista, https://de.statista.com/statistik/daten/studie/258626/umfrage/bevoelkerung-in-europa-nach-art-der-wohnung/
[148] Cf. Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (Retrieved: 07.12.2022b)

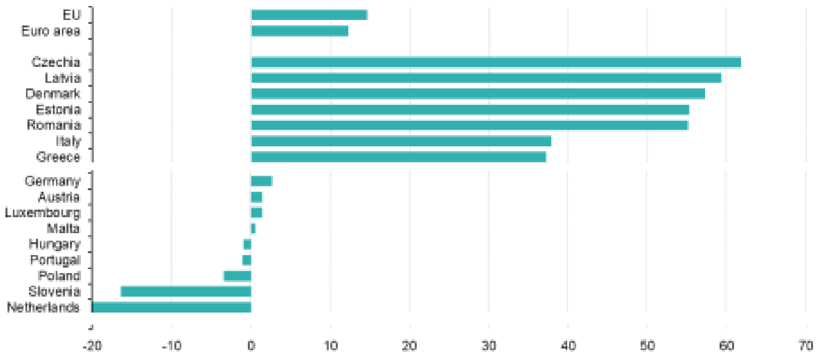

Figure 31: electricity price development Europe[149]

All these factors contribute to a very different picture across Europe regarding electricity prices. As demonstrated in Figure 32 the average price per kWh for consumers rose to around 0,25 €·kWh^{-1}. Denmark, Belgium, and Germany are experiencing the highest prices, while in the Netherlands the prices are close to their long-time average, due to governmental aid.[150]

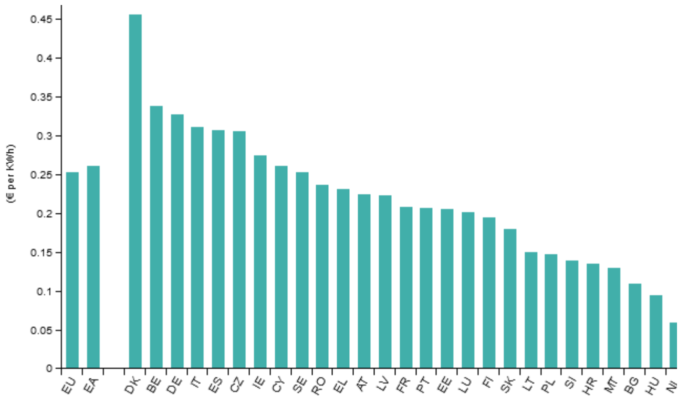

Figure 32: average electricity prices for household consumers, first half 2022[151]

Electricity prices are essential for further considerations. In the case of sorption energy storage, especially business cases with Power-to-Heat (P2H) applications are severely affected by these developments, as they may rely on low energy prices for energy supply. However, amortization times may be reduced if reference energy prices are higher.

Natural gas is also a major energy source in Europe. As natural gas prices rise, consumers and companies may consider replacing existing natural gas heating systems. Especially in Northern and Eastern European nations, gas prices are rising dramatically. Natural gas prices need to be considered further in this thesis. This is due to distinct reasons. On the one hand, a major share of the rise in electricity prices can be traced back to rising natural gas prices in Europe. This is because gas-powered plants are used as peak plants to compensate for supply shortages. Also, gas is a major source of energy

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149 Source: Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (Retrieved: 02.12.2022a)

150 Cf. Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (Retrieved: 02.12.2022a)

151 Source: Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (Retrieved: 02.12.2022)

in many European countries, including the Netherlands, Austria, and Germany. Natural gas can be seen as a reference energy source for sorption heat storage, as gas is a primary source of heating in many European countries and may be used in combination.

4.1.2 Status-quo of industrial and service sector

When shifting the focus to the industrial side, a completely different picture can be seen. As Figure 33 shows, other than in residential use, different types of energy and distinct levels of heat are needed. Space heating in industrial applications has the same requirements as residential heating. Process heating up to 100 °C uses the same technologies as domestic heating. Analogies for the results of FlexModul can be drawn accordingly. Process heating up to 200 °C can also use similar technologies, while heat storage becomes significantly more difficult. Comparable technologies, however, cannot be applied to processes heated up to 500 °C and even beyond. Even though the share of energy needed is remarkably high in high-temperature applications, reaching up to 50% of the total heat demand, this area will not be further discussed in this thesis due to the different technologies necessary. As a potential source of energy for low-temperature applications, waste heat from high-temperature processes can be used and applied. This is according to the principle of exegetic cascading and optimization. The service sector is remarkably like household applications. Energy is primarily used for heating and sometimes cooling.[152]

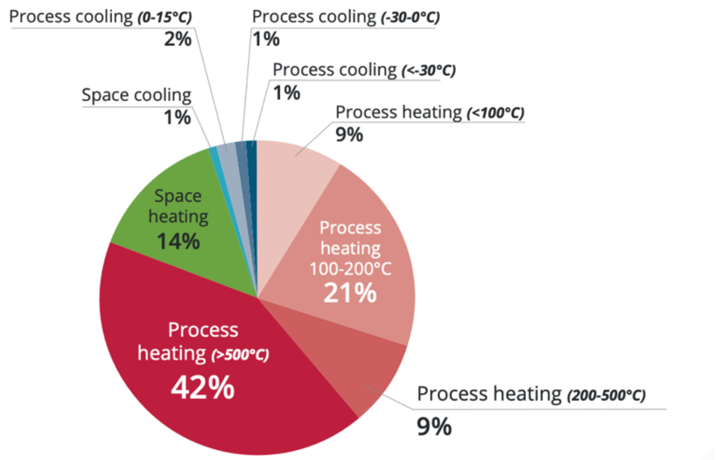

Figure 33: industry heating and cooling demand of EU28 in 2019[153]

4.1.3 Winter-summer price comparison

For the power-to-heat scenario to unfold its potential, the underlying assumption, in which seasonality in electricity prices exists, needs to be proven. There must also be a way to capitalize on this opportunity. The assumption was mainly based on higher solar and renewable energy production in summer, as well as lower consumption. As

[152] Cf. Heat Map Europe, https://heatroadmap.eu/wp-content/uploads/2019/03/Brochure_Heating-and-Cooling_web.pdf (Retrieved: 19.12.2022)
[153] Source: Heat Map Europe, https://heatroadmap.eu/wp-content/uploads/2019/03/Brochure_Heating-and-Cooling_web.pdf (Retrieved: 19.12.2022)

described by STØRDAL S. ET AL. in 2022, a high seasonality is presented. To demonstrate this difference, the team compared the future wholesale prices of electricity in Germany and Scandinavian countries traded on the European Energy Exchange AG (EEX) and the National Association of Securities Dealers Automated Quotations (NASDAQ). Figure 34 shows the results. The figure started in January 2006 and ended in December 2021. The authors concluded that a seasonal spread exists, and a simple long-short strategy can generate positive returns. In the end, the team tried to understand why this spread was present, however, no conclusion was drawn. A higher presence of this trend is evident in the Nordic Countries, where seasonally dependent hydro power is prevalent. This was mentioned as a possible cause.[154]

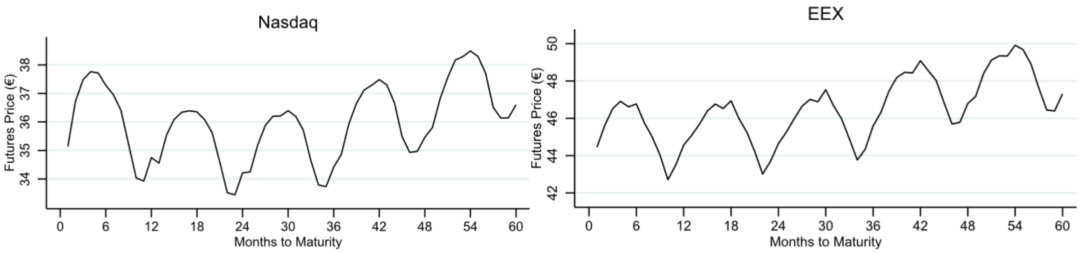

Figure 34: EEX and Nasdaq electricity future prices vs. months to maturity[155]

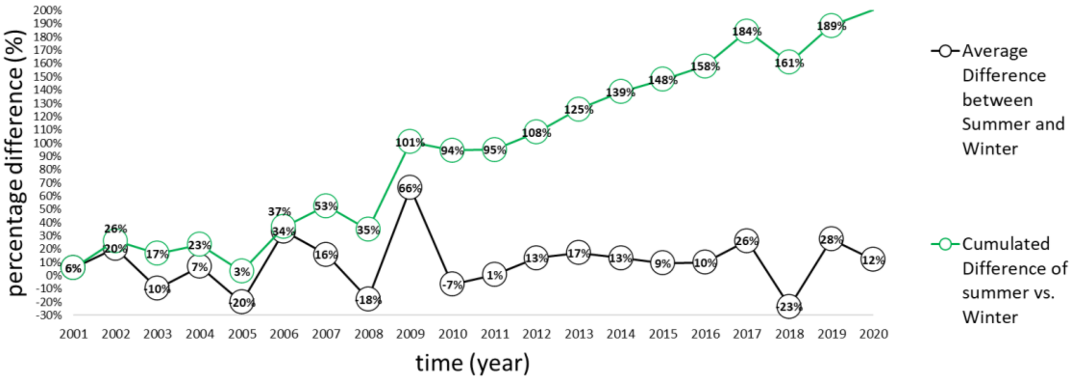

Figure 35: comparison of summer and winter electricity prices in Germany, year over year and cumulated difference[156]

In Figure 35 the relative difference between electricity prices in summer (Q2 and Q3) versus winter prices (Q4 and Q1 of the following year) is displayed. Year over year, no clear trend can be seen. However, the cumulative returns show a clear trend. The cumulative return of summer versus winter arbitrage in a simple long-only strategy is given. In summer electricity prices are lower than in winter over a longer period. As the basis for this analysis the EEX quarter average future prices for base load were used.

There are other major developments on the market relevant to electricity prices, that could exaggerate this seasonality. It is expected that the shift towards heat pumps will lead to an increase in electricity demand in the winter months. Battery electric vehicles (BEV) are another factor that should be considered. In Europe, the number of newly registered vehicles is steadily increasing, which will most likely lead to an increase in

154 Source: Størdal, S. et al. (2022), p. 7
155 Source: Størdal, S. et al. (2022), p. 7
156 Source: own illustration, Data source: EEX

electricity demand. On the supply side, the building of new PV plants has massively increased in recent years. PV production is usually higher in summer months than in winter months. The demand for electricity will likely increase in winter months due to the widespread application of heat pumps. The increase in heat pumps and PV can be clearly seen in Table 5. Developments around BEV and PV are demonstrated in Figure 36.

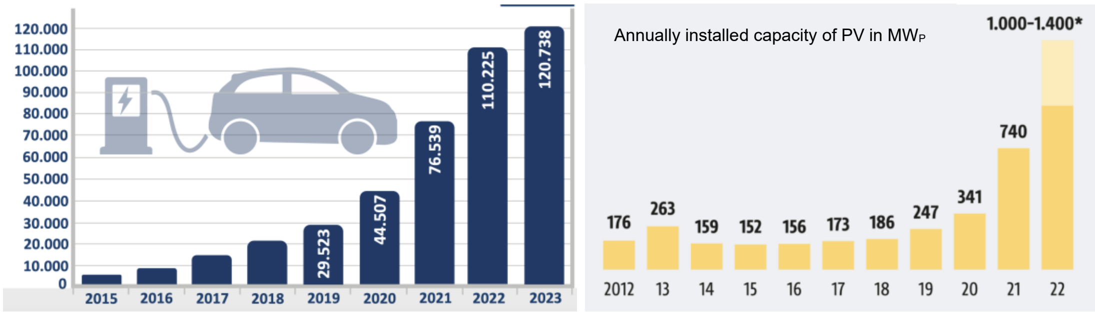

Figure 36: new registrations of BEVs and annually installed PV capacity[157,158]

Therefore, the winter-summer price spread is expected to increase. As a result, electrical arbitrage on a seasonal scale will likely become more profitable than they already are. Variable price products are a prerequisite to capitalizing on this opportunity and must be available to households. As of March 2023, no such product is available in Europe.

4.1.4 Commercial comparison of sorption materials

When choosing materials, it is important to consider not just technical factors, but also the financial side, which determines whether a product is technically viable for real-world application. AGHEMO ET AL. compared a vast number of materials from a technical and economical perspective. These materials will be used in this thesis as a basis for comparison, especially materials that can operate in closed system within a solid bed. In the past Zeolite 13X and silica gels were used as reference materials at AEE INTEC. While having a solid understanding of these materials new and better materials were seen as a key factor in the future success of this technology. As of 2023 many different materials have been tested, however, no real competitors to the existing working pair were found. Many potentials have been presented and tested. As described in previous chapters, composite materials, salt hydrates, hydrophobization and other working pairs have been extensively investigated. Only promising potentials were shown, but no real performance gains could be achieved over many cycles. In general, long-term stability was always a problem. As of now, it seems that Zeolite 13X and similar structures such as Zeolite NaY are the most performing materials.

These materials are also competitive. As shown in Table 6, the prices of sorption materials vary widely. More exotic materials cost up to 100 €·kg^{-1} and are not a viable

[157] Source: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, https://infothek.bmk.gv.at/photovoltaik-boom-oesterreich-2022-gigawatt-marke/ (Retrieved: 21.04.2023)
[158] Source: Bundesverband Elektromobilität Österreich, https://www.beoe.at/bestand/ (Retrieved: 21.04.2023)

alternative to common materials. So, Zeolite still poses a financially viable alternative and is used in this thesis as well as many other research projects.

Table 6: commercial prices of main sorption materials[159]

Material	Price (€·kg^{-1})	Material	Price (€·kg^{-1})
Zeolite 4	1,20	Silica gel	1,20
Zeolite 13X	1,60	Expanded Clay	0,20
Zeolite Y	1,10	Pumice	0,15
Zeolite NaX/LiX	1,80	AlPO	100,00
Zeolite NaY	2,90	SAPO	100,00
Bentonite	0,17	FAPO	100,00
Vermiculite	0,16	MWCNT	4,00
Activated Alumina	0,94	MOF	250,00

4.1.5 Price limits according to market research

For successful product development and marketing, it is necessary to find out how much customers are willing to pay. In this case pricing for upgrades to existing heating systems as well as for replacement systems needs to be investigated. In 2021, the Austrian Energy Agency (AEA) conducted a thorough analysis in this field in cooperation with the Austrian Research Institute SORA. The core question was whether end consumers were willing to invest in renewable heating technologies. It also asked how much they were willing to invest and how much funding from the public sector is necessary. As a result of this study, the consumers were categorized into four categories. Open-minded, Insecure, Pioneers and Refusers. The pioneers and open-minded make up just above 50% and can be seen as the target group of FlexModul. The group of insecure individuals accounts for another 24%. They might not be part of the target group now, however, as technology evolves and other people adopt the updated technology, they can eventually become part of the target group as well. The refusers are either not willing to invest at all or refuse advancing technologies outright.[160] Therefore, they are not considered in any marketing plan.

The cost of a heating system is highly relevant to consumers. According to the study by AEA, the willingness ranges from 5k € in quantile 1, over 10k € in median and 20k € in quantile 3, as is shown in Figure 37. This limits the investment cost for a storage system significantly. Ideally, the whole storage system cost can be kept below 10k € to have enough market potential. The market is significantly smaller if prices are 20k € or above. As a starting point, prices of 20k € are acceptable and can lead to successful market deployment in household applications. Early adopters make up up to 20% of the total market. [161] It appears that this pricing puts them within reach. Both large segments on the consumer side and the public and service sector can be targeted if further price reductions are possible. When looking at subsidy requirements, higher prices can be

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[159] Source: own illustration, adapted from: Aghemo, L. et al. (2023), p. 143

[160] Cf. Lechner, H. et al., https://www.energyagency.at/fileadmin/1_energyagency/projekte/erneuerbare_waerme/moteevate_endbericht.pdf (Retrieved: 06.03.2023)

[161] Cf. Lechner, H. et al., https://www.energyagency.at/fileadmin/1_energyagency/projekte/erneuerbare_waerme/moteevate_endbericht.pdf (Retrieved: 06.03.2023)

tolerated if public subsidies can be achieved for this technology. If subsidies are given for this solution, more awareness of the product might be achieved. This might boost sales and help tolerate higher prices.

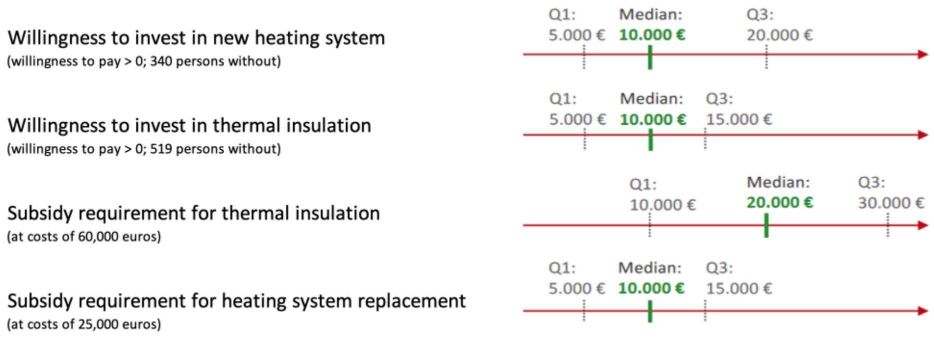

Figure 37: willingness of end consumers to invest in heating solutions[162]

4.1.6 Summary and results of the market analysis

In the housing market a clear trend is visible. Renewable heating systems are steadily taking over. The ban on coal and oil in Austria has stopped new heating systems and they are now slowly driven out of the market. Other countries are taking similar measures. Grid-based heat sources like natural gas and district heating are steady and increasing. Solar and heat pumps have the largest increase. So natural gas, even though it is usually fossil-based, still has relevant market shares, and needs to be considered in future calculations as a reference.

Based on the market review the baseline in the form of use cases for the simulation will now be defined and explained. In the practical part of this work, the use cases are simulated using Polysun by VelaSolaris. This is a common software tool for heating system simulation in households and small systems. Simulation results are used for detailed financial analysis. The results of this simulation are then compared with those of FlexModul.

In all use cases a standard single-family home will be used as a reference, with 4 inhabitants. As a location, a central valley in the Austrian Alps is used. Natural gas, air-water heat pumps, thermal solar collectors and photovoltaic are the technologies deployed. The load profiles are the same across all use cases. Hydraulic schemes are optimized for each technology to ensure accuracy. FlexModul is then added to the model. In Table 7 a detailed overview of the use cases is provided. The performance comparison was made based on energy balances. First, an annual comparison was carried out to estimate the potential for energy storage, use, and saving. The calculation was refined and made on a monthly, daily, and hourly basis. Similarly, use cases 7 and 8 compare the performance of a PV only system and a PV with a battery system, simply comparing them.

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[162] Source: Lechner, H. et al., https://www.energyagency.at/fileadmin/1_energyagency/projekte/erneuerbare_waerme/moteevate_endbericht.pdf (Retrieved: 06.03.2023)

Table 7: use cases for simulation[163]

	Name	Additional	Detailed Explanation
Use case 1	Natural Gas	without PV	the heat is fully supplied by a natural gas heating system
Use case 2	Natural Gas	with PV	the heat is fully supplied by a natural gas heating system; electricity demand is supplemented by PV
Use case 3	Heat Pump + Solar	without PV	solar as primary heat source; HP as auxillary
Use case 4	Heat Pump + Solar	with PV	solar as primary heat source; HP as auxillary; electricity demand is supplemented by PV
Use case 5	Natural Gas + Solar	without PV	heat is supplied by solar; supplemented by natural gas heating system
Use case 6	Natural Gas + Solar	with PV	heat is supplied by solar; supplemented by natural gas heating system; electricity demand is supplemented by PV
Use case 7	PV	without Battery	reference for PV without battery
Use case 8	PV	with Battery	reference for PV with battery
Use case 9	Heat Pump	without PV	heat pump as only heat source
Use case 10	Heat Pump	with PV and Battery	heat pump as only heat source; electricity demand is supplemented by PV; battery system is used

For operation modes, two scenarios were considered. The first scenario considers FlexModul as seasonal storage with one discharge per year. It became obvious very early on that seasonal storage with a cycle count of one was very undesirable. With a maximum capacity of 400 kWh and an electricity price of 0,48 €·kWh-1 a maximum of 192 € can be saved per year for the use case. This is assuming the energy delivered to the system was available at 0 €·kWh^{-1}. At an investment cost exceeding 10k € this does not present a very attractive solution for home or business owners. A more dynamic approach needed to be found. So, the first operating scenario was adapted. The system is always charged when PV surplus is available and normally fed into the electricity grid. Heat from FlexModul is retrieved whenever heat is needed and not available from solar. This dramatically increases the number of cycles and usage and savings.

The second business case, as presented in an earlier section, has the target to supply flexibility to the market. This is why it relies heavily on market regulation. As research has shown, consumers cannot participate in flexibility markets. The provision of this service is not paid for and cannot be monetized explicitly. Therefore, the business case as proposed is not possible to be monetized as of early 2023. However, it is expected that this business case can also deliver when the market regulations change and open. For the future regulations are expected to change according to EAG, who is working on products and contracts along with Austrian regulators. For a simulation or estimation of the effectiveness of this business case prices or estimation would be needed. Unfortunately, no details are published yet. Therefore, the second business case will no longer be investigated.

4.2 Simulation of the business case

In this section the business cases will be discussed. First, performance data from the real system is collected. Based on this data, business cases, performance, energy savings and general energy flows through the system are calculated and simulated.

[163] Source: own illustration

4.2.1 Performance tests

Based on the plant layout described in section 3, tests were conducted to find out if the operating use cases, as proposed, are technically viable. The following results are based on the data gathered during the tests of February and March 2023. The test plant was reduced in size to 133 kg Zeolite 13XBF compared to future real-life applications with 1800 kg of Zeolite 13X.

During the charging process, for which the results are presented in Table 8, 41.6 kWh were put in the system through a 16-kW heating rod. The charging temperature was limited to 160 °C. 13.7 kWh could be directly used during the charging process through condensation heat and was used for DHW. The remaining sensible heat energy of 10.8 kWh could also be used for DHW. During discharging 4.16 kWh of electric power were put into the system, to obtain the stored energy from the storage. 21.4 kWh could be used from the storage in total. In the Figure 38, the significance of waste energy use can be seen. Without the use of waste heat less than 50% of the energy put into the system are available to the user. When using the otherwise wasted heat for heating or DHW applications, losses can be reduced drastically.

These results are demonstrated in the Sankey Diagram in Figure 38, which is a schematic representation of the results and the aggregated data, with numbers in percent. Losses occur along all process steps. Most notably, sensible heat that is generated during charging and discharging is highly dependent on the operating mode and can either occur as usable or lost heat. If a discharge is followed by a phase of no operation high losses occur.

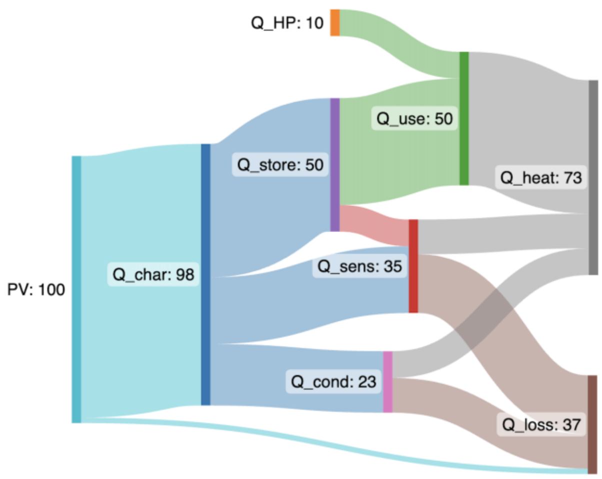

Figure 38: energy balance of the roundtrip, numbers in %[164]

In Table 8 the overview of the representative tests can be seen. Run 0 was a test run to gather information about exact temperatures and timing. Three independent runs were conducted afterwards. Even though the amount of energy put through the system varied significantly, RTE were similar. A total efficiency of around 60% can be seen. The data for Run 0 with low temperature are the most promising and are a baseline for future tests.

[164] Source: own illustration

For the current setup under normal conditions, this result is not achievable in automatic operation.

Table 8: results from the test runs in March 2023[165]

	Unit	Run 0 - Short Low Temperature	Run 0 - High Temperature	Run 0 without waste heat usage	Run 1	Run 2	Run 3
$\sum Q_{in}$	kWh	45,77	82,30	45,77	48,25	37,05	36,36
$\sum Q_{out}$	kWh	46,39	44,45	21,47	31,23	21,21	21,23
RTE	%	101,35%	54,01%	46,91%	64,73%	57,25%	58,38%
Q_{store}	kWh	17,31	17,31	17,31	16,98	11,15	10,89

So, the following performance data was calculated based on the first and second runs. In the planned system a total capacity of 200 kWh can be reached at charging temperatures between 150 and 180 °C. Charging can be done with up to 16 kW while discharging performance achieving 2 kW of continuous power. This is based on the demonstration plant, which will be higher in the real plant. The power output takes some time for the system to reach full power with a PG of 1500 $W \cdot h^{-1}$ while it is possible to stop the system immediately if needed, as demonstrated in Figure 39.

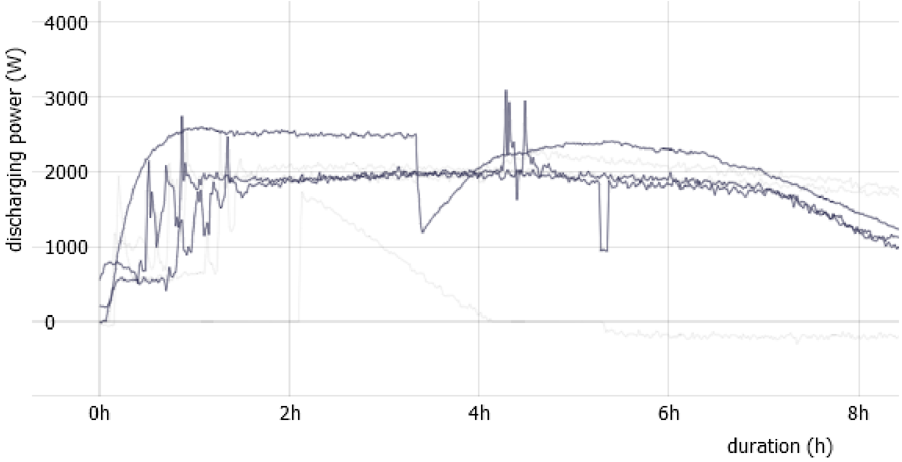

Figure 39: discharging power over several runs[166]

These results are connected to several problems. Determining the exact quantity of losses that occurred during the charging and discharging process was not accurately possible due to measuring errors. In general, the results are on the side of usable energy. Temperature measurements and related performance data were up to 20% lower than the real values due to piping losses before the measuring points. Also, it was not possible to separate relevant energy flows, such as the heat flow from the surrounding into the heat pump. As a result, the results are distorted and influenced on this side. Usable energy is altered to the negative and input energy is influenced to the positive.

[165] Source: own illustration
[166] Source: own illustration, created with Visplore

4.2.2 Simulation of Business case 1

For the simulation of the business cases and the reference use cases, the following assumptions, as shown in

Table 9, are based on the market analysis and standard load profiles (SLP). As the reference for all use cases a standard house that was built around 2000 was used, with state-of-the-art technology of that time. It is assumed, that newer houses are often equipped with HP or solar heating. For older houses it is assumed, that a general overhaul of the heating system might be necessary. For houses around 2000 a simple upgrade of the heating system might be an attractive solution. For simplicity purpose, the SLPs were used directly from the simulation software Polysun.

To get a good understanding of the applicability of a 400 kWh FlexModul system a deployment of the system in the described house was simulated. The following approach was used. First, from an annual point of view, it was calculated how much energy is available for charging the sorption storage as a surplus from PV, how much energy can be used during discharging, and how much energy of the waste energy could be used. This approach was then refined to get a quarterly picture, then a monthly, then a daily, an hourly and at last a 15-minute approach. The results showed that a more granular view close to a real minute-based simulation delivered better results.

Table 9: assumptions for simulation and the business cases[167]

Assumptions	
Area of House	140 m^2
People in household	4
year of construction	2000
Annual electricity Demand	4500 kWh
Annual heating demand	16000 kWh
Annual DHW demand	4500 kWh
PV power	10 kW_p
Battery capacity	10 kWh
natural gas boiler power	12,5 kW
HP Power	15 kW_{therm}
Storage tank size	1000 l

When looking at the system of use case 10 as an example, where a HP, solar, PV and a battery are in use, with the sorption storage deployed, significant reduction in energy use from the grid can be seen. In Figure 40 the reduction of the original energy use in violet compared to the use of external energy in green can be seen. In the months of May through September external energy supply is not necessary at all.

[167] Source: own illustration

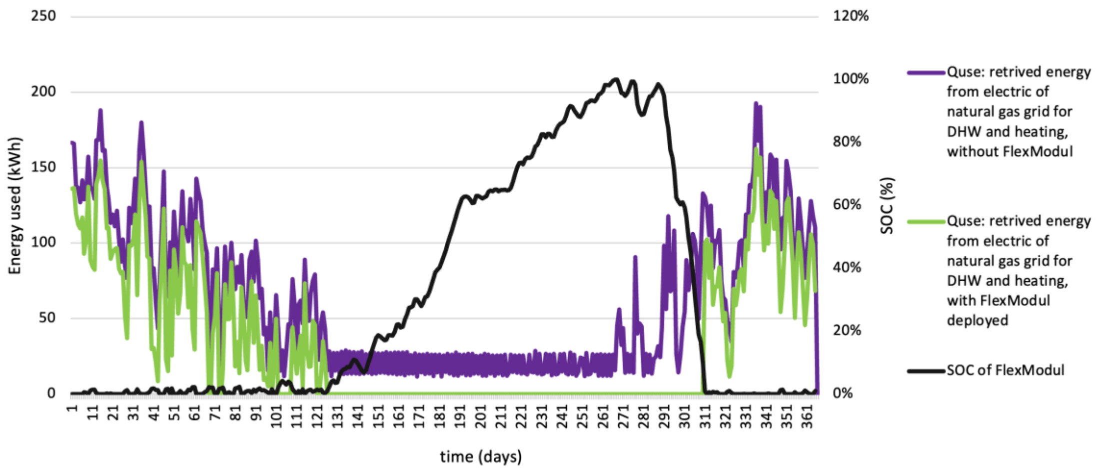

Figure 40: reduction of energy use through FlexModul[168]

In Figure 41 the performance characteristics of the system 10 with FlexModul are shown. The starting SOC was set to 10%. Starting in May, the system is charged up until October, when consumption finally overtakes the available energy from PV. Discharging of the system was present all along the year and can be seen in grey. In June the power to the system overtakes the consumed power. A real increase in SOC can now be seen and the system is steadily charged. Although the SOC is close to zero at the end of the year, some energy can still be used since some days do have a surplus of PV.

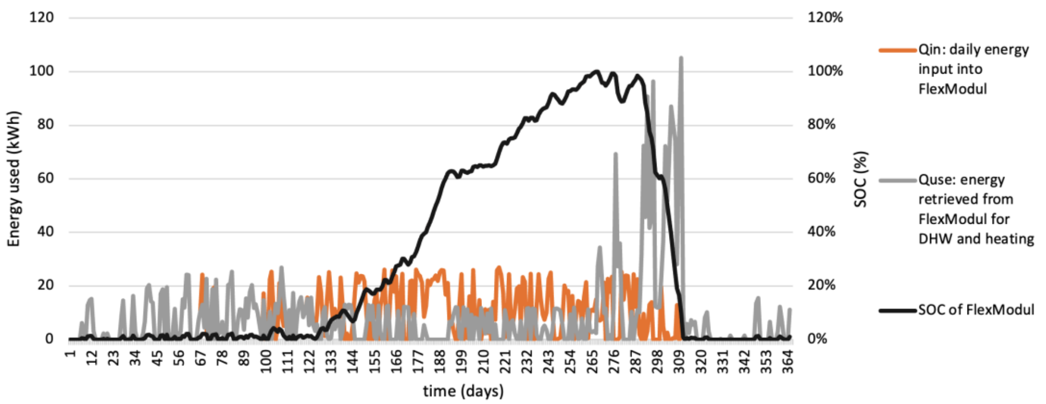

Figure 41: charging and discharging[169]

In Table 10 the results of the simulation for use cases where FlexModul is deployed in addition to other systems are shown. Only the use cases with PV and a heating system are shown, as only here FlexModul is applicable. Significant saving could be seen in a natural gas heated solution. At current prices, a reduction of cost of around 250 € p.a. in HP solutions, while in a reduction of cost up to 2k € p.a. can be seen in natural gas solutions. It becomes evident that FlexModul becomes more attractive as the prices increase. The results presented show a clear picture, that the system can be successfully deployed.

[168] Source: own illustration
[169] Source: own illustration

Table 10: Use Case analysis with FlexModul[170]

	Unit	NG + PV	HP + Solar + PV	NG + Solar + PV	HP + PV
		Use Case 2	Use Case 3	Use Case 6	Use Case 10
Surplus used	kWh	6271	2826	6261	2826
Energy Stored in Flexmodul	kWh	3136	1413	3130	1413
Reduced Primary Energy Usage	kWh	6442	825	2323	825
Reduced Cost p.a. @0,08€/kWh	€	201	90	200	90
Reduced Cost p.a. @0,30€/kWh	€	753	339	751	339
Reduced Cost p.a. @0,50€/kWh	€	1254	565	1252	565

4.3 Cost estimation

In this section the cost structure of the system will be described. First a top-down cost approach will be conducted, to define the financial thresholds, in which the pricing must be. Then, bottom-up cost estimation will be presented. Finally, optimization of the cost structure is proposed and discussed.

4.3.1 Top-down cost estimation

When comparing various storage capacities ranging from 50 kWh to 2000 kWh, it becomes visible, that a maximum of usable energy can be reached. At a capacity of 1120 kWh, no more energy can be stored in the system in a dynamic operating mode over the course of a year, in the context of the use case 10 as previously described. When comparing the energy saved at 50 kWh capacity and at the maximum of 1120 kWh, as shown in Figure 42, it can be seen, that the maximum capacity only stores 1.6 times the energy of the lowest at 22.4 times the capacity. This raises the question if high capacities are even necessary. Possible solutions to more energy stored are to increase the PV size, which in return would increase overall CAPEX. This assumption, however, is not the scope of this thesis.

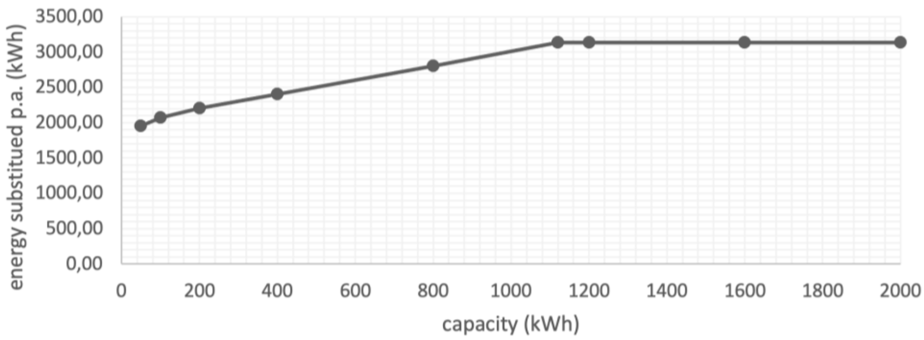

Figure 42: energy saved from system versus capacity of the system[171]

For the top-down approach, it needs to be considered how much a system of a given size can cost to reach an NPV of 0 within a given range of time. It is assumed that amortization times up to 7 years are acceptable for households and industry, according

[170] Source: own illustration
[171] Source: own illustration

to the market research described at the beginning of section 4. Also, amortization times of 20 years and 30 years are demonstrated as a comparison, to compare the system on a lifetime basis. According to the results of previous projects by AEE INTEC a total lifetime of 20 years to 30 years is possible. For a basic estimation an electricity price for substitute energy $c_{energy,subst}$ of 0.08 €·kWh^{-1}and of 0.30 €·kWh^{-1} are used. The first one was the average electricity price before 2022 and the latter one was the average electricity price across Europe at the beginning of 2022. The results of this calculation are presented in Table 11.

Table 11: maximum acceptable prices at given amortization times[172]

reference energy cost	amortization time	acceptable investment	CAPEX per kWh
0,08 €·kWh^{-1}	7 year	€ 1.340,32	3,35 €·kWh^{-1}
0,08 €·kWh^{-1}	20 years	€ 3.804,71	9,51 €·kWh^{-1}
0,08 €·kWh^{-1}	30 years	€ 5.678,71	14,20 €·kWh^{-1}
0,30 €·kWh^{-1}	7 year	€ 5.026,19	12,57 €·kWh^{-1}
0,30 €·kWh^{-1}	20 years	€ 14.267,68	35,67 €·kWh^{-1}
0,30 €·kWh^{-1}	30 years	€ 21.295,17	53,24 €·kWh^{-1}

As demonstrated higher prices are beneficiary for the system. Considering current energy prices low amortization times can be achieved if enough energy is put through the system. According to AEA, enthusiasts tend to accept higher amortization times. This leads to the assumption, that at current energy prices, 14k € to 20k € are acceptable and FlexModul can be marketed at this price range. If higher energy densities and superior operating modes can be developed, prices up to 30k € can be tolerated and possibly marketed.

4.3.2 Bottom-up cost estimation and reduction of cost

For the financial analysis, a DCF-model approach was used. The assumptions can be found in the annex. As the macro-economic analysis has not been a field of research, this area is out of scope for this thesis. Some assumptions, however, need to be made. The assumptions were based on previous calculations of similar projects and ignored the covid crisis as well as the Russo-Ukrainian conflict. First, the cost structure of the system needs to be analyzed. As presented in Figure 43 the cost structure of the system highly depends on certain single components. The sorption material itself, the internal and external heat exchanger, the evaporator, and condenser as well as the HTF pump are the biggest contributor of costs. Sensors can be a relevant part as well, depending on how far the models can be developed and how accurate sensors need to be. The number of sensors required is also a major factor. In one of the two given setups a DWHP is necessary as a low-temperature heat source. This significantly adds to the system cost. In future systems this HP can be spared and is a fast and easy cost reduction.

172 Source: own illustration

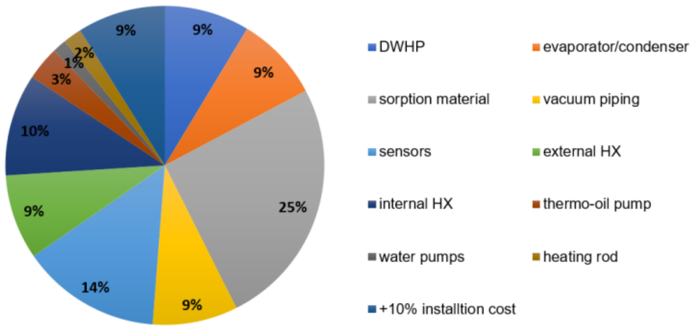

Figure 43: cost structure of the plant based on averaged price assumptions[173]

To optimize plant costs, there are many measures that can be taken. A transition from custom components to standard components will reduce costs.

CAPEX is the main dealbreaker besides performance. By reducing the investment cost of sorption storage significantly, the technology might be suitable for end users and industrial applications. The first step toward cost reduction was a detailed analysis of each component's cost. Detailed results of this analysis can be found in the Annex.

The largest cost is the internal heat exchanger, sensors, the HP, the evaporator and condenser unit, the vacuum piping and the two external heat exchangers. Heat exchangers are essential components that cannot be replaced. For reliable operation, sensors are essential. Modeling and simulation are necessary to reduce the number of sensors required and are therefore beyond the scope of this thesis.

It is possible to alter the internal heat exchanger significantly. By increasing the distance between plates and pipes, material and welding costs can be reduced. Charging and discharge performance will be reduced. However, this does not pose a significant disadvantage. In heating applications constant loads can compensate for peak performance, if a small thermal energy storage is used for short term load balancing.

The heat transfer fluid pump is necessary for the desorption process, where temperatures of up to 180 °C are supplied. Through a reduction of the temperature to below 150 °C, this pump can be spared. The cost can be reduced from approximately 1k € to below 200 €. Also, the HTF can be dispersed, which makes handling easier and eventually, if mass produced, production as well as maintenance noticeably cheaper.

For low-temperature energy, a DWHP is used. This can be eliminated if other sources of low temperature are present, for example ground heat, pond water, waste heat etc. If a HP is necessary, cheaper solutions are possible. By using pool heat pumps a cost reduction from about 3k € to just 1k € can be achieved.

On the material side major improvements can be achieved. Suppliers usually produce at lower cost, if larger quantities are produced, due to the economics of scale. This can only be achieved if the system is mass-produced. Therefore, it will not be further discussed in this thesis. However, a careful selection of the supplier is necessary, as price differences of over 300% were seen in the research process of this thesis.

[173] Source: own illustration

When adding up the improvements that seem possible in the short term, an overall reduction in CAPEX of close to 50% can be achieved. Prices of around 14k € are possible under these assumptions. In the updated cost structure, it becomes clear that the sorption material has become the single largest cost of the plant.

Several areas have not yet been fully inspected in this project, including the external HX, the DWHP, the installation cost, and the EC unit. Depending on the project, this may be an area of intense focus in the future. In the long run it is expected that mass production and widespread adoption of this technology will reduce prices significantly. Prices around 10k € are targeted and seem possible.

4.4 Analysis and discussion of results

In this section the results of this chapter will be summarized, KPIs will be presented, and conclusions will be drawn.

4.4.1 Results and KPIs of FlexModul

In Table 12 the results of the relevant key performance indicators are displayed. From a technological perspective, the energy density is high and sufficient for household applications. As a result, the given system has a large capacity and can significantly impact a household's energy balance. While having relatively high charging temperatures, which can be seen as a disadvantage compared to other sorption technologies, the usable temperature level or discharge temperature is also high and is therefore suitable for DHW applications. The system's charging power was relatively high, but could be even greater, if needed through upgrading the heating rod. This could enable the system to deliver flexibility for the electric grid if these services become available on the market in the future. The discharge power of 2 kW was low, but will increase in real deployed systems, because the planned HX will be significantly larger. A continuous load of 2 kW can, however, be sufficient to supply modern homes during the winter. Financial KPIs look promising. LCOS and LCOH are already in an area where they will be competitive soon. Yet, other KPIs are not competitive in the current environment. Future developments will, however, improve these metrics.

Table 12: KPIs of FlexModul[174]

KPI	Results	KPI	Results
E_{stor}	300 - 400 kWh	PG	1500 $W \cdot h^{-1}$
ρ_{Stor}	150 - 200 $kWh \cdot t^{-1}$	RTE	60 - 80%
T_{Ch}	150-180 °C	P_{char}	16 kW
T_{disch}	20-50°C	$P_{dischar}$	2 kW

The total CAPEX for the system was in the range of 14,7k € at best and 23k € at worst, while OPEX was close to zero. This assumes that no electricity purchase was needed

[174] Source: own illustration

and only PV energy, that could no longer be fed into the grid was used. So overall storage cost $c_{storage}$ between 36 €·kWh^{-1} and 76 €·kWh^{-1} are achievable. Comparing to the initial target of the project of 27 €·kWh^{-1}, this was not yet fully achieved. However, major steps towards market readiness were successfully achieved.

The technological side delivered interesting and promising results. The plant has demonstrated that these systems can be deployed in the field. Both charging and discharge phases showed stable performance, with steady and predictable characteristics. The results were repeatable. Both manual and automatic operation could yield similar results, showing that the system can be used reliably. The system was controllable and worked under the required conditions. The calculated performance data revealed efficiency problems. Unfortunately, some measurements were flawed. For future systems this needs to be addressed, losses need to be minimized and measurements fixed and verified.

4.4.2 Analysis and discussion of results

To investigate the potential for seasonal energy storage energy balances were established for simulated systems. When looking at those energy balances, the whole system was too small to substitute relevant amounts of energy for November, December, and January. Therefore, a short-term approach was used. This worked quite well as short- to mid-term storage with the initially planned 400 kWh. However, energy independence over a year is not possible with this or significant higher capacity in the given scenarios. It is during September and October that the storage is fully charged. Heating demand rises in November and peaks in December and January. Consequently, the amount of energy needed soon exceeds the amount of energy stored in the system. Therefore, the system has no or little effect on the household in winter months. To supply energy in these months, the storage capacity needs to reach 3000 to 5000 kWh, depending on the system. Also, the PV system would need to be increased significantly to reach heating energy levels in winter.

For seasonal storage with low cycle numbers, energy savings cannot offset the investment cost. Only if cycle numbers increase and storage can be used throughout the year, will this technology become attractive for household customers. Essentially, the financial analysis and KPIs show the system as short-term storage of thermal energy with a seasonal aspect and indicate that this might be a possible application for this technology. When looking at amortization times of 20 to 30 years, the acceptable prices for the system are in the area where it can be delivered as of 2023. When considering amortization times, as required by the service and industry sectors, the market becomes significantly more competitive. To reach these amortization times, CAPEX needs to be reduced significantly or performance limits need to be pushed. Potentials to improve in both areas have been identified, which seem possible and might make this technology interesting for these sectors.

To sum up, the system presented in this thesis works technologically while only being financially feasible for very specific applications. Improvements need to be made to deploy this system in the wider application, which will likely be achievable in the coming years.

5 Summary and Outlook

This thesis investigates if it is possible from a technological standpoint to store heat in a closed fixed bed sorption heat storage on a long-term or seasonal basis and if so, if it is financially feasible to do so on a household scale either by using surplus electric energy from a photovoltaic system or from surplus energy in the electric grid as a service.

An extensive literature review laid the groundwork for later research on this topic. Zeolite was confirmed as a suitable material. This was followed by a market analysis to analyze marketing options. Also, other technologies with which sorption storage can be used together were investigated. For a proper understanding of the project's financial side, a thorough investigation of possible components was conducted. Suppliers provided fitting parts and prices. Prices for sorbent materials were difficult to obtain and varied greatly.

On the technological side of this thesis, attention has been given to sorption energy storage. Many systems have demonstrated in the past that this technology can store heat seasonally. At the system level, the demonstrator plant demonstrated that the efficiencies were high enough to justify this storage technology. It is possible to achieve round-trip efficiencies that make this technology interesting for various markets. Energy losses must be actively managed to achieve this.

Overall, the performance was satisfactory, and reasonable round-trip efficiencies could be achieved. The newly developed parts of this project were successfully deployed and delivered sufficient performance. From a material standpoint, Zeolite proved very usable. The idea of seasonal thermal energy storage with a single cycle in a year or at a low cycle rate needed to be abandoned as it was financially not feasible. It was then demonstrated that a more dynamic approach to short-term heat storage with storage times of several days to several months is possible and technologically feasible. Transferring energy from summer to winter is only feasible if the system operated throughout the year. The financial analysis of this operating mode continues to raise questions and highlights the need for improvements on the financial side. The target cost of storage of 27 $€\cdot kWh^{-1}$ has not been reached in this project. However, it was pushed closer to the target than ever before, reaching 36 $€\cdot kWh^{-1}$.

To sum up, FlexModul can technically be used. Financial performance is questionable and will certainly need much more focus in future projects, to be successfully deployable and to reach the competitive targets of this project.

On the material side, it is anticipated that improvements in coatings and novel materials will push the limits of this technology. Significantly higher energy densities are expected to be reached. Steps towards mass production can reduce prices and improve financial performance. Under the present market regime, however, sorption technology is not generally applicable and financially feasible for seasonal energy storage. This is based on the layout presented in this thesis.

Changes in the market structure, the possibility of supplying flexibility to the electric grid as a customer, governmental subsidies, and negative electricity prices alongside many other factors could make this technology very appealing to a broad field of customers. In the face of fluctuating renewable energy technologies, the unique selling proposition of storing energy seasonally may become more appealing to customers.

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Appendix

Annex 1: Comparison of available long-term storage solutions (Source: own illustration)

Name	Technology	Cost range	Storage capacity	Link
Home power Solutions	hydrogen	85k € - 125k €	Not available	https://www.homepowersolutions.de/produkt/
LAVO	hydrogen	No price available	Not available	https://www.lavo.com.au/
Cleen Energy	hydrogen	No price available	Up to 330 kWh per Bundle	https://cleen-energy.com/wasserstoffspeicher/
Johann	hydrogen	No price available	300-1500 kWh	https://www.elements-energy.at/
GKN Hydrogen	hydrogen	No price available	165-8500 kWh	https://www.gknhydrogen.com/
Flextherm	Latent heat	2k € – 4k €	2-10 kWh From 2k $€\cdot kWh^{-1}$ To 400 $€\cdot kWh^{-1}$	https://flamcogroup.com/de/catalog/pufferspeicher-und-warmwasserbereitung/thermische-batterien/flextherm-eco/flextherm-eco/groups/g+c+p+a+view

Annex 2: Cost Structure of the plant, cost estimation of components used in FlexModul (Source: own illustration)

Component	Cost Estimation lower limit	Cost Estimation upper limit
DWHP	€ 1.500,00	€ 5.000,00
evaporator/condenser	€ 1.500,00	€ 2.500,00
sorption material	€ 3.978,00	€ 7.344,00
vacuum Piping	€ 2.000,00	€ 2.500,00
sensors	€ 700,00	€ 2.500,00
external HX	€ 1.500,00	€ 2.500,00
internal HX	€ 2.000,00	€ 2.500,00
thermo-oil pump	€ 500,00	€ 2.000,00
water pumps	€ 300,00	€ 400,00
heating rod	€ 200,00	€ 550,00
Sum	€ 14.178,00	€ 27.794,00

Annex 3: Overview of available heat pumps on the market (Source: own illustration)

Type	Producer	Cost (€)	P (kW)	URL
Air-Water HP	LG	€ 5 494,00	7	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Air-Water HP	LG	€ 5 800,00	9	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Air-Water HP	LG	€ 7 657,00	12	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Air-Water HP	Logatherm	€ 14 425,00	7,6	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Air-Water HP	Vaillant	€ 10 114,00	7	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Air-Water HP	Saunier Duval	€ 7 250,00	7	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
DWHP	Austria Email	€ 2 519,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Aquafit	€ 2 398,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Stiebel Eltron	€ 2 303,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Saunier Duval	€ 2 220,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Vaillant	€ 1 918,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Ochsner	€ 3 041,00	-	https://www.badshop-austria.at/heizung/warmwasserbereitung/waermepumpe/
DWHP	Ochsener	€ 2 597,00	-	https://www.badshop-austria.at/heizung/waermeerzeuger/waermepumpen-4074
Pool HP	Steinbach	€ 1 048,00	1,45	https://www.pools.shop/de-AT/suche?keyword=W%C3%A4rmepumpe
Pool HP	Steinbach	€ 800,00	0,84	https://www.pools.shop/de-AT/suche?keyword=W%C3%A4rmepumpe
Pool HP	Steinbach	€ 468,00	0,85	https://www.pools.shop/de-AT/suche?keyword=W%C3%A4rmepumpe
Pool HP	BWT	€ 349,00	0,5	https://www.apoolco.at/pools/pooltechnik/poolheizung/waermepumpen/bwt-mini-pool-waermepumpe-shp2.5-bwt
Pool HP	BWT	€ 1 259,00	0,68	https://www.apoolco.at/pools/pooltechnik/poolheizung/waermepumpen/pool-waermepumpe-inverter-connect-ic-68-6-8-kw-30-m3-pools-bwt-bwt

Annex 4: Suppliers of Zeolite (Source: own illustration)

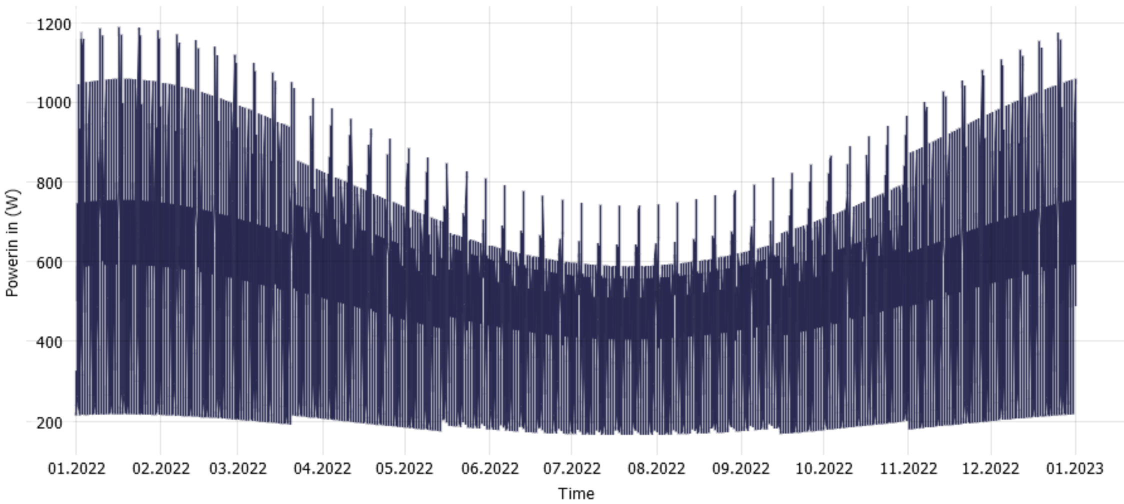
Area	Company	Description	Link
China	Anten Chemical Co., Ltd.	is a leading producer of synthetic sodium silicate, specialized zeolite powder and other performance materials serving the chemical, petroleum, catalysts, adsorbents, detergent, pulp and paper, water treatment, and construction markets	https://antenchem.com/about/
China	Huiying Chemical Industry Co Ltd	We has been specializing in synthetic zeolites powders,3a/4A/5a/10x/13x molecular sieves powder,Synthsis Zeolite detergent grade and special zeolites	http://www.xmzeolite.com/
China	Huiying Chemical Industry Co Ltd		http://www.qzhuiying.com/en/
China	ZeoliteMin	is a leading supplier of natural zeolite clinoptilolite in China	https://zeolitemin.com/
France	Arkema		https://www.arkema.com/france/en/
Germany	CWK Chemiewerk Bad Köstritz GmbH	Industrial production of zeolitic molecular sieves	https://www.cwk-bk.de/de/
Germany	Kurt Obermeier GmbH & Co. KG	UOP Molekularsieves	https://www.obermeier.de/
Germany	ZEOCEM, AG	Extraction and processing of natural zeolite and production of products based on natural zeolite	https://www.zeocem.com/de/
Germany	Zeo-Tech	Environmentally friendly refrigeration, heating and drying technology with zeolites and water	https://www.zeo-tech.de/
International	Albemarle	Speciality zeolites	https://www.albemarle.com/
International	Clariant	Advanced zeolite powders	https://www.clariant.com/de/Corporate/Search
International	PQ Corporation	-	https://www.pqcorp.com/
International	Prayon	-	https://www.prayon.com/en/
International	UOP Honeywell	-	https://uop.honeywell.com/en
International	Zeochem	-	https://www.zeochem.com/
International	Zeolyst	Zeolyst is a leading global supplier of specialty zeolite powders and catalysts.	https://www.zeolyst.com/
USA	Bear River Zeolite	mines, processes, packages and sells natural zeolite	https://www.bearriverzeolite.com/
USA	CB Minerals	Distributor of synthetic and natural grades zeolites. Meets ISO 9000 standards.	https://cbminerals.com/
USA	Grace -W. R. Grace & Co.-Conn.	Zeolite Molecular Sieves	https://grace.com/
USA	Reade Advanced Materials	Distributor of natural and synthetic zeolites. Packaged in plastic bags, super sacks, bulk trucks or railcars. Suitable for odor control, industrial absorbents or fillers, gas absorption, soil remediation, wastewater filtration, flocculating agent, animal feeds,	https://www.reade.com/
USA	Sorbent Media Inc.	Manufacturer of adsorbents. Offers silica gel in 1-3 mm to 2-5 mm sizes, activated alumina in 1/16" to ¼ in sizes, and molecular sieves from 20 x 40 to 4 x 8 bead sizes. Also offers silica gel pouches, moisture control gun safe bags, and hearing aid	https://www.sorbentmedia.com/
USA	St. Cloud Mining, Inc.	St. Cloud Mining is the largest producer of high quality, high purity natural zeolites in North America, and the only company in that owns and operates a complete suite of unique zeolite mineral deposits.	https://www.stcloudmining.com/
USA	Zeo, Inc.	The Leader in Natural Zeolite Products and Technology	https://zeoinc.com/

Annex 5: Available oil pumps for the required applications (Source: own illustration)

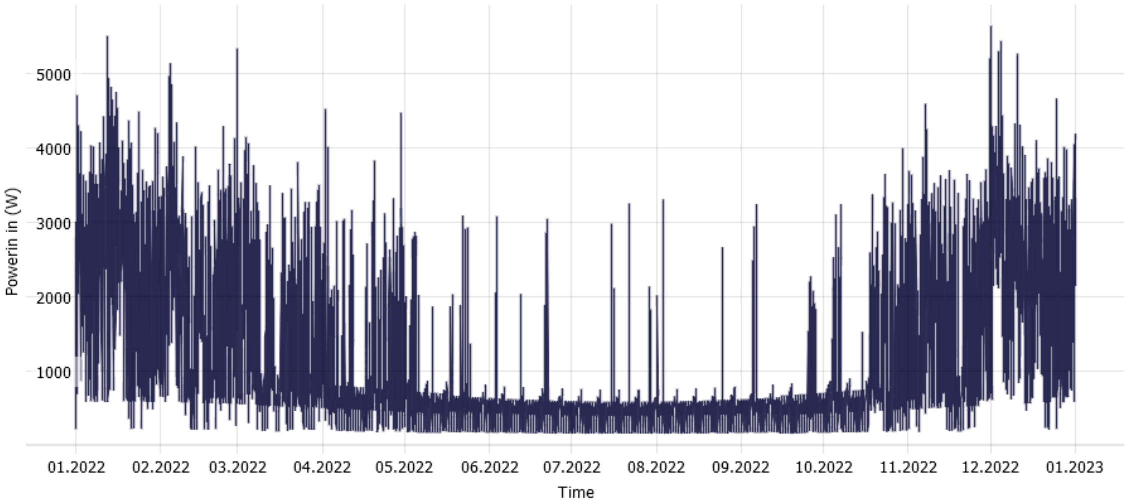
Producer	Cost	Country of Origin	Link
Julabo	€ 14 500,00	Germany	https://www.julabo.com/de/produkte/zubehoer/zusatzheizer-zusatzpumpen-erweiterungskits/booster-pump-8810020
McMaster	€ 1 910,00	USA	https://www.mcmaster.com/ethylene-glycol-pumps/maximum-temperature~range~~-1646784438324/maximum-flow-rate~4-5-gpm/
McMaster	€ 741,00	USA	https://www.mcmaster.com/pumps/for-use-with~ethylene-glycol/maximum-flow-rate~4-5-gpm/maximum-temperature~range~~-1646784438324/maximum-flow-rate~7-gpm/maximum-flow-rate~8-9-gpm/
Sinntec	€ 811,00	Germany	https://www.sinntec.de/OeL-Zahnradpumpe-400V-17-l-min-1400-U-min-10-bar
Sinntec	€ 673,00	Germany	https://www.sinntec.de/OeL-Zahnradpumpe-400V-5-l-min-1400-U-min-10-bar
Alunac	€ 153,00	Ukraine	https://bts.net.ua/de/pumping-equipment-distillery/high-temperature-pumps/vikhroviy-maslyaniy-nasos-wm-033s-220v-30-c-200-c/

Annex 6: Available heat transfer fluids (Source: own illustration)

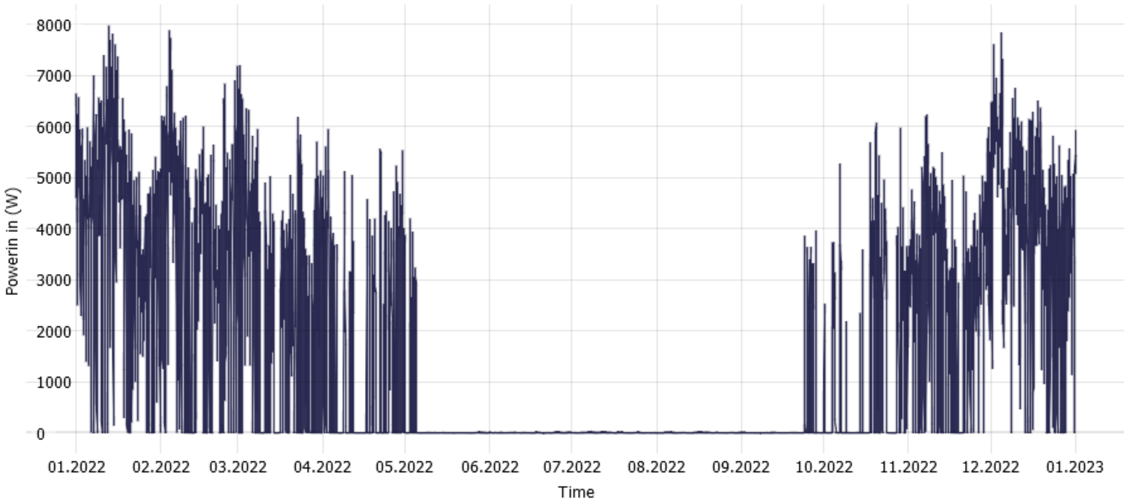
Product	cost per liter	T_{max} in °C	Link
Ravenol 32	€ 5,50	320	https://www.ravenol-shop.de/ravenol-waermetraegeroel-32?number=1330210-020
Coracon Sol	€ 5,99	102	https://www.solardirekt24.de/hochtemperaturbestaendige-solarfluessigkeit-coracon-sol-5hf-bis-240c-4374-v-10-50.10?c=2964
Staub & CO Silberman Solarliquid HT gebr.	€ 5,29	103	https://www.solardirekt24.de/10-50-liter-hochtemperaturbestaendige-solarfluessigkeit-solarliquid-ht-bis-2600c-20025001-v.10?c=2964
Marlotherm SH	€ 25,00	340	https://marken-schmierstoffe.de/products/marlotherm-sh-25kg-waermetraeger



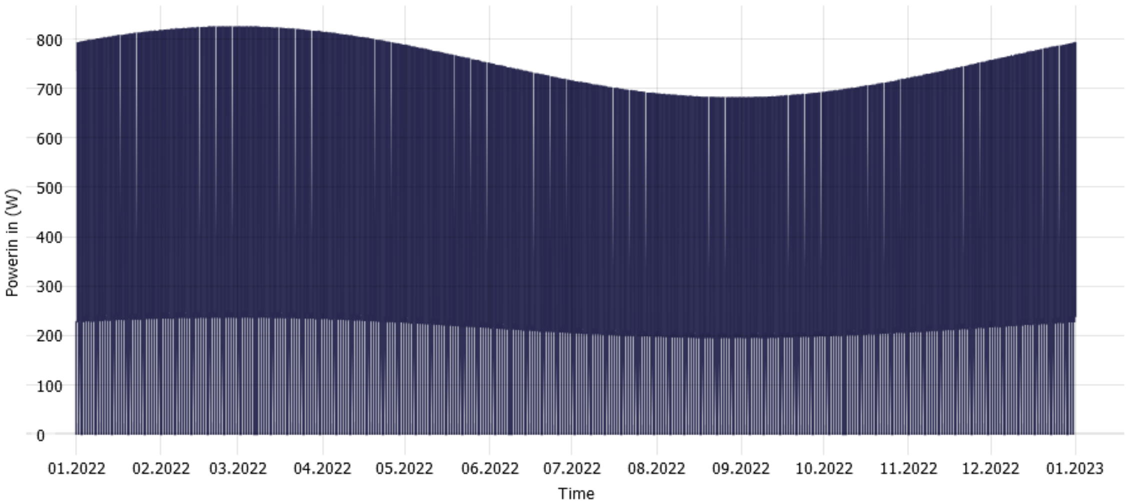
Annex 7: SLP for the electric load of house (Source: own illustration; Source of Data: Polysun by VelaSolaris)



Annex 8: electric load of house with heating (Source: own illustration; Source of Data: Polysun by VelaSolaris)



Annex 9: heating demand of house (Source: own illustration; Source of Data: Polysun by VelaSolaris)



Annex Figure 10: energy demand for DHW (Source: own illustration; Source of Data: Polysun by VelaSolaris)

Annex 11: LCOS Calculation and Results (Source: own illustration)

Levelized Cost of Storage (LCOS)

Assumptions	
Initial Investment Cost (€)	15.000
Operations and Maintenance Costs (€)	100
O&M Growth Rate (%)	2,00%
Annual Electricity Cost (€)	-
Annual Energy Output (kWH)	3.000
Project Lifespan (years)	10
Discount Rate (%)	3,00%
Entry Date	31.12.22

Total Costs	**Entry**	Construction	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations
Date	31.12.22	31.12.23	31.12.24	31.12.25	31.12.26	31.12.27	31.12.28	31.12.29	31.12.30	31.12.31	31.12.32
Year Frac (From Start Date)		–	1	2	3	4	5	6	7	8	9
Initial Investment	15.000	-	-	-	-	-	-	-	-	-	-
O&M Costs	-	-	100	102	104	106	108	110	113	115	117
Fuel Costs	-	-	-	-	-	-	-	-	-	-	-
Discount Factor		1,000	0,971	0,943	0,915	0,888	0,863	0,837	0,813	0,789	0,766
Present Value of Costs	**15.000€**	**-**	**97€**	**96€**	**95€**	**94€**	**93€**	**92€**	**92€**	**91€**	**90€**
NPV of Total Costs	**15.841€**										

Total Energy Output	Entry	–	1	2	3	4	5	6	7	8	9
Yearly Output	-	-	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Discount Factor	0,000	1,000	0,971	0,943	0,915	0,888	0,863	0,837	0,813	0,789	0,766
Present Value of Energy	-	-	2.913	2.828	2.745	2.665	2.588	2.512	2.439	2.368	2.299
Present Energy	**23.358kWh**										

LCOE	**0,68€/kWh**
	678,16€/MWh

Annex 12: LCOS sensitivity analysis (Source: own illustration)

		kWh p.a.								
	635,35€/MWh	**200kWh**	**400kWh**	**800kWh**	**1 200kWh**	**1 600kWh**	**2 000kWh**	**2 400kWh**	**2 800kWh**	**3 200kWh**
CAPEX	€ 12 000,00	8245,85	4122,92	2061,46	1374,31	1030,73	824,58	687,15	588,99	515,37
	€ 14 000,00	9530,18	4765,09	2382,55	1588,36	1191,27	953,02	794,18	680,73	595,64
	€ 16 000,00	10814,52	5407,26	2703,63	1802,42	1351,82	1081,45	901,21	772,47	675,91
	€ 18 000,00	12098,86	6049,43	3024,72	2016,48	1512,36	1209,89	1008,24	864,20	756,18
	€ 20 000,00	13383,20	6691,60	3345,80	2230,53	1672,90	1338,32	1115,27	955,94	836,45
	€ 22 000,00	14667,54	7333,77	3666,88	2444,59	1833,44	1466,75	1222,29	1047,68	916,72
	€ 24 000,00	15951,88	7975,94	3987,97	2658,65	1993,98	1595,19	1329,32	1139,42	996,99
	€ 26 000,00	17236,22	8618,11	4309,05	2872,70	2154,53	1723,62	1436,35	1231,16	1077,26
	€ 28 000,00	18520,55	9260,28	4630,14	3086,76	2315,07	1852,06	1543,38	1322,90	1157,53
	€ 30 000,00	19804,89	9902,45	4951,22	3300,82	2475,61	1980,49	1650,41	1414,64	1237,81

Annex 13: LCOH Calculation and Results (Source: own illustration)

Levelized Cost of Heat (LCOH)

Assumptions	
Initial Investment Cost (€)	15.000
Operations and Maintenance Costs (€)	100
O&M Growth Rate (%)	2,00%
Annual Fuel Costs (€)	50
Annual Energy Output (kWH)	6.000
Project Lifespan (years)	10
Discount Rate (%)	3,00%
Entry Date	31.12.22

Total Costs	**Entry**	Construction	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations
Date	31.12.22	31.12.23	31.12.24	31.12.25	31.12.26	31.12.27	31.12.28	31.12.29	31.12.30	31.12.31	31.12.32
Year Frac (From Start Date)		–	1	2	3	4	5	6	7	8	9
Initial Investment	15.000	-	-	-	-	-	-	-	-	-	-
O&M Costs	-	-	150	153	156	159	162	166	169	172	176
Fuel Costs	-	-	50	50	50	50	50	50	50	50	50
Discount Factor		1,000	0,971	0,943	0,915	0,888	0,863	0,837	0,813	0,789	0,766
Present Value of Costs	15.000	-	194	191	189	186	183	181	178	175	173
NPV of Total Costs	**16.650€**										

Total Energy Output	Entry	–	1	2	3	4	5	6	7	8	9
Yearly Output	-	-	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Discount Factor	0,000	1,000	0,971	0,943	0,915	0,888	0,863	0,837	0,813	0,789	0,766
Present Value of Costs	-	-	5.825	5.656	5.491	5.331	5.176	5.025	4.879	4.736	4.599
Present Energy	**46.717kWh**										

LCOE	**0,36€/kWh**
	356,41€/MWh

Annex 14: LCOH sensitivity analysis (Source: own illustration)

	kWh p.a.									
	335,00€/MWh	**2 000kWh**	**3 000kWh**	**4 000kWh**	**5 000kWh**	**6 000kWh**	**7 000kWh**	**8 000kWh**	**9 000kWh**	**10 000kWh**
CAPEX	€ 12 000,00	876,58	584,38	438,29	350,63	292,19	250,45	219,14	194,79	175,32
	€ 14 000,00	1005,01	670,01	502,50	402,00	335,00	287,15	251,25	223,34	201,00
	€ 16 000,00	1133,44	755,63	566,72	453,38	377,81	323,84	283,36	251,88	226,69
	€ 18 000,00	1261,88	841,25	630,94	504,75	420,63	360,54	315,47	280,42	252,38
	€ 20 000,00	1390,31	926,87	695,16	556,12	463,44	397,23	347,58	308,96	278,06
	€ 22 000,00	1518,74	1012,50	759,37	607,50	506,25	433,93	379,69	337,50	303,75
	€ 24 000,00	1647,18	1098,12	823,59	658,87	549,06	470,62	411,79	366,04	329,44
	€ 26 000,00	1775,61	1183,74	887,81	710,24	591,87	507,32	443,90	394,58	355,12
	€ 28 000,00	1904,05	1269,36	952,02	761,62	634,68	544,01	476,01	423,12	380,81
	€ 30 000,00	2032,48	1354,99	1016,24	812,99	677,49	580,71	508,12	451,66	406,50